SEA-TITAN: A REVOLUTIONARY POWER TAKE-OFF TECHNOLOGY

M. Neri

Europe's 2050 Energy Strategy targets a reduction of greenhouse gas emissions by 80%-95% compared to 1990 levels with renewable energy accounting for at least 64% and up to 97% of the electricity consumed.

The Ocean Energy Forum produced the Ocean Energy Strategic Roadmap which has estimated that 100GW of ocean energy capacity could be deployed, producing around 350TWh of electricity meeting up to 10 % of Europe's demand by 2050.

The ocean energy is based on the use of Wave Energy Converters (WECs) which produce electricity from waves. The core of a WEC is the Power Take Off (PTO), which transforms mechanical movements into electrical energy.

www.seatitan.eu

Introduction

On 12 December 2019 the European Council, taking note of the Communication of the European Commission on the European Green Deal, endorsed the objective of achieving a climate-neutral EU by 2050, in line with the objectives of the Paris Agreement and in the light of the latest available science and of the need to step up global climate action. In crude numbers, the Europe's 2050 Energy Strategy targets a reduction of greenhouse gas emissions by 80%-95% compared to 1990 levels with renewable energy accounting for at least 64% and up to 97% of the electricity consumed.
To achieve a reliable increase of the proportion of energy consumed to be coming from renewable energy sources, a well assorted mix of natural energy sources is needed. Today, photovoltaics, wind and hydroelectric power represent the vast majority of the available renewable energy.

In addition, the Ocean Energy Forum (OEF) produced the Ocean Energy Strategic Roadmap (November 2016) which has estimated that 100GW of ocean energy capacity could be deployed in Europe by 2050, producing around 350TWh of electricity meeting up to 10 % of Europe's demand by 2050. The achievement of this target would contribute significantly to the diversification of the renewable energy sources.

This ocean energy is based on the use of so-called Wave Energy Converters (WECs) which produce electricity from waves. The core of a WEC is the Power Take Off (PTO), which transforms mechanical movements into electrical energy.

The Sea-Titan project aims at developing a simpler, more robust and cost effective multi-technology compatible PTO.

The project, born in 2018, has received funding from the European union's Horizon 2020 research and innovation programme and brings together 11 partners from 7 European countries.

The main goal of the project is to design, build and test a prototype of a new configuration of PTO, but in parallel with this goal, it aims at exploring the possibility of developing a PTO based on a superconducting machine.

The efficiency of a PTO can be described by a parameter: the force density (Force to Mass Ratio Capacity). Increasing this parameter is the primary objective for the ocean energy industry. A superconducting PTO can significantly increase the force density whilst also reducing the size.

A superconducting solution is studied by ASG Superconductors in collaboration with CIEMAT. In particular, ASG has been involved in the definition of the superconducting wire and in the estimation of the amount of ac losses in the wire during operation of the PTO.

Wave Energy Converters

Wave ocean energy is acquired using Wave Energy Converters (WECs). Presently, there are a significant number of competing Wave Energy Converter (WEC) technologies using different concepts and designs.

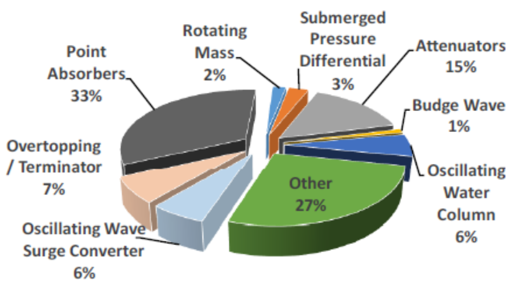

Figure 1 Different WEC typologies and their distribution rate.

They can be classified based on their location (Onshore – Nearshore – Offshore) and on their orientation with respect to the wave (Attenuator – Terminator – Point Absorber).

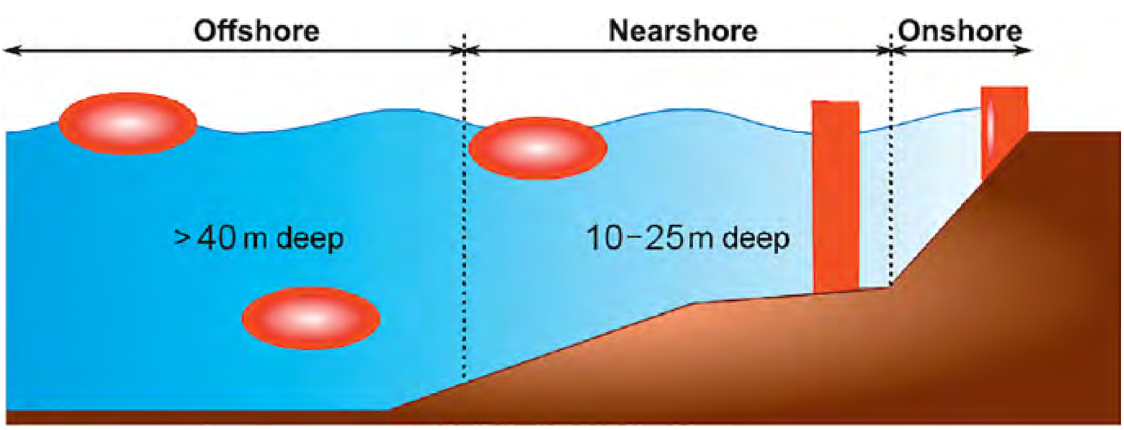

Figure 2 Classification of the WEC typologies based on location.

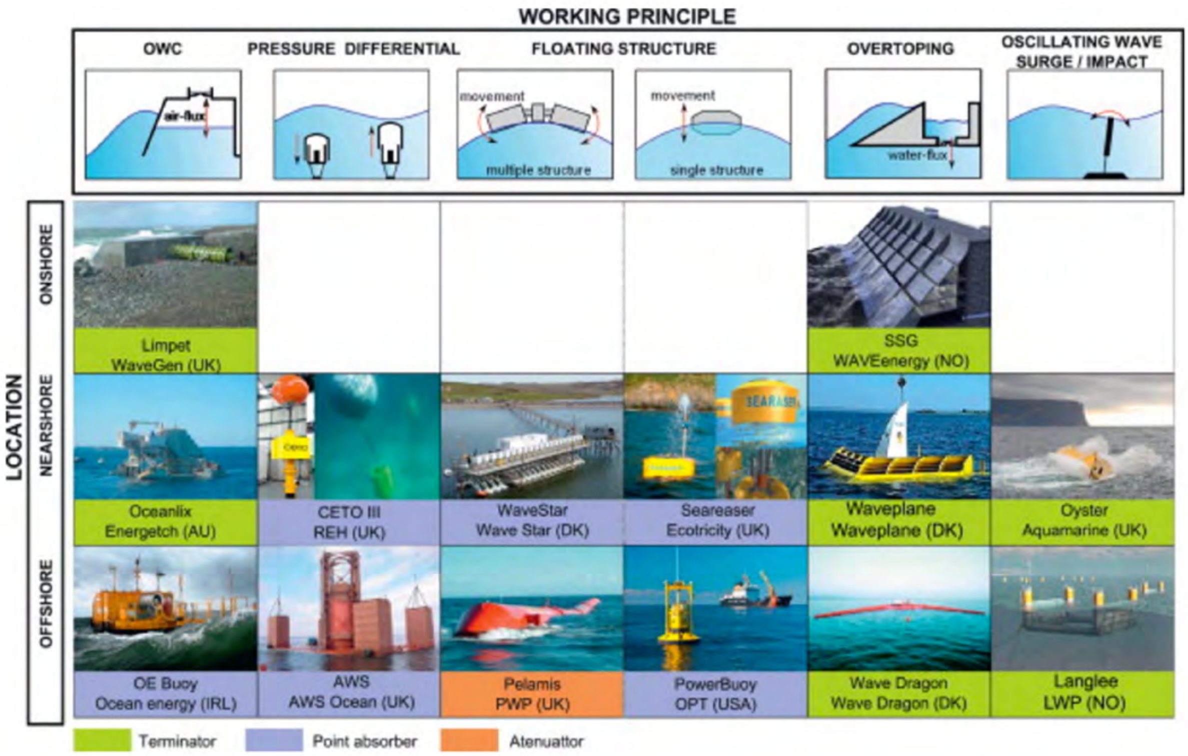

Figure 3 Classification of WEC typologies based on location and working priciple.

The Point Absorber type WECs are the most numerous; they are simple, omni-directional and easy to deploy.
Among these WEC topologies, a Heaving Point Absorber (HPA) is a two body WEC based on the relative movement of two bodies: one is stationary or pseudo-stationary and it is called the Spar, while the other is a moving body and it is called the Float, floating at the sea surface and excited by wave force.

The working principle of an HPA is quantified by means of an equivalent model, based on a quite simple concept. There are two forces acting on the Float of the WEC, one produced by the wave and the other by the PTO, both acting upon a mechanical system characterized by its impedance. Alternatively, the problem can be seen as two generators (corresponding to each force; wave and PTO) which are coupled through an impedance and the question is to adjust the value of the PTO force to extract the maximum amount of energy from the wave.

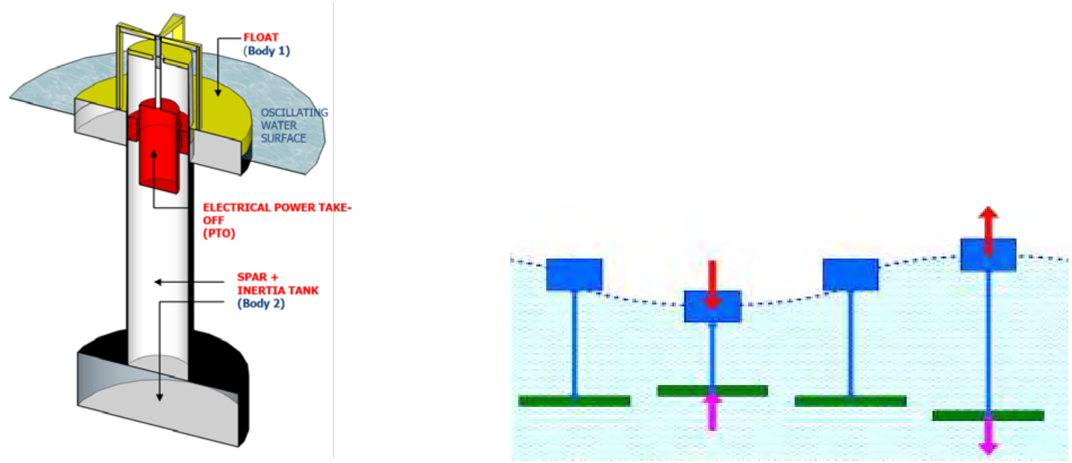

Figure 4 Configuration of a Heaving Point Absorber.

Power Take Off

The PTO is the device which converts the mechanical energy from the wave into electricity. The conversion can be done in several steps or in a single step by using a linear electricity generator. In this latter configuration the PTO is known as a Direct-Drive system.

Direct-Drive machines are all based on a Translator/Stator configuration which balances the transverse forces.
The forces in ocean energy are produced by the waves. In order to maximize energy production, the system must work close to resonance. In this configuration, the Stroke, the maximum amplitude of the translator motion, can be high even if the waves are small.

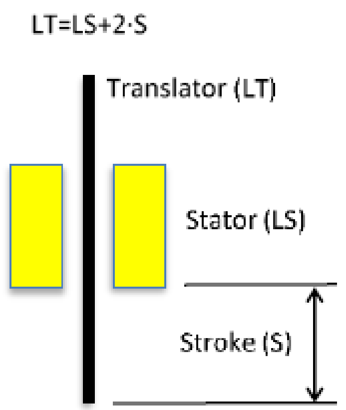

Figure 5 Direct-Drive machine scheme.

Any electrical machine is defined by the Shear Stress, the force produced per unit surface of its airgap. This parameter is proportional to the product of the electric load of the machine (expressed in kA/m) times the magnetic load of the machine (expressed in Tesla).
There are several topologies of linear machines, differing primarily in the way the magnetic field is generated: by means of permanent magnets or electromagnetic coils.
In marine applications, permanent magnets are not appropriate because they are very delicate components, prone to corrosion.

Given all these considerations, the Sea-Titan project has focused its work on the development of a new PTO for a Heaving Point Absorber WEC, based on a Switched Reluctance Machine (SRM).
In this machine configuration there is an Active side (coils generating the magnetic field) and a Passive side (iron). The two sides move with respect to each other. At a given amount of total current, the force increases according to the reluctance of the iron path.

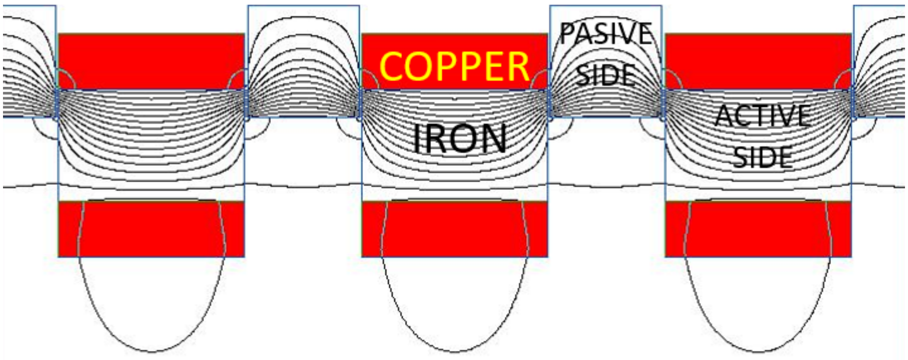

Figure 6 A Switched Reluctance Machine has an Active side (copper and iron pole) and a Passive side (iron) moving one respect of the other.

The goal of the project is to enhance the force density with reduced impact on the volume of the machine.
Two different approaches have been identified. The first approach is to design, built and test a new configuration of a machine using conventional wire.
The second approach is to consider using superconductivity to increase the electrical output of the machine, eliminating in practice the losses while improving the shear stress significantly. This will be considered as a long-term option for a future generation of Direct Drive PTOs.

Superconducting PTO

Superconducting coils in a linear machine can tolerate higher current densities which generate higher forces, without increasing the volume of the machine.
Indeed, the advantage of using a superconducting machine as a PTO in general and a superconducting SRM machine in particular can be easily explained considering that the produced force is proportional to the product of the magnetic flux density times the total current in the coil phase. In a non-superconducting coil, there is a strict limit to the current that the coil can transport but in a superconducting one that limit is much higher and this means that very big currents can be transported in small volumes. The difference between a non-superconducting machine and a superconducting one, both with iron in their magnetic circuit, is that although they work at similar magnetic flux density levels (slightly higher in the superconducting case), this small variation in the field (in the range of 10% to 20%) implies a tremendous variation of the current and consequently of the force.

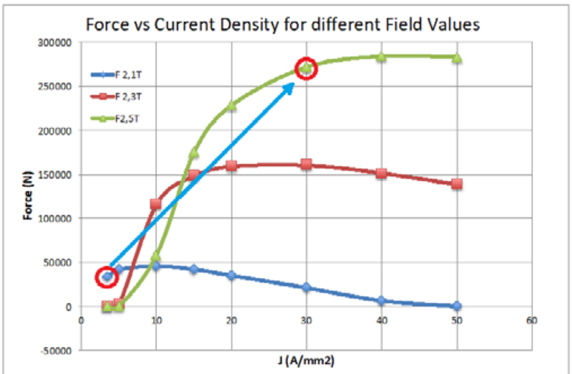

Figure 7 Force vs Current Density for 3 values of B. For a normal conductor, working above 3-4 A/mm^2 is not possible (the best option is the blue curve). For a superconducting machine it is possible to achieve 30 A/mm^2, jumping to the green curve.

Using superconductivity in PTOs provides a fine example of the paradigm of superconductivity: on the one hand, the reduction of space and the increase of efficiency and force which are very useful advantages for this application but, on the other, the increased complexity, particularly in such a difficult environment as operating in the ocean.
Nowadays, various types of superconducting machines have been proposed, most of them in the sector of wind energy. Some solutions are based on High Temperature Superconductors (HTS), but there is at least one based on magnesium diboride (MgB_2).
Focusing on Superconducting Linear Machines, the number of developments is small. The most well-known machine is the Japanese Maglev which uses a Long Stator Synchronous Motor with superconducting excitation.

Most of the other proposals are based on using Synchronous Linear Motors with a normal conducting Long Stator and a superconducting Translator based on bulk HTC permanent magnets to avoid superconducting coils in the moving parts.
In the wave energy sector there has until now been only one superconducting solution, based on a Linear Synchronous Machine with superconducting excitation and normal conducting stator.
There are different critical issues with superconducting machines.
The first issue is related to alternating current (ac) losses.
Superconducting materials are characterized by zero resistance below a critical temperature. This means that in a superconducting coil there is no power dissipation producing joulean heating.

$$P_{Joule}=RI^2$$

If the coil is powered by direct current (dc), R is zero and no power is generated, so there are no losses. However, if a superconductor is exposed to a time-varying field, as is the case with an alternating current (ac) source, power is generated inside the superconductor. This wasted power, called ac loss, produces heat which must be extracted, increasing the complexity of the arrangement. Superconductors are very sensitive to the frequency of the time variation: for standard frequencies (50 Hz) the ac losses are simply inadmissible. Indeed, all the previously mentioned PTO proposals only use superconductivity on the dc side.
Nevertheless, using superconductivity in both ac and dc sides of the machine is becoming increasingly attractive, providing a big reduction in the size and efficiency of the machine.
The second issue is related to cooling. Superconducting coils must be installed in a cryostat to keep them at cryogenic temperatures. Related to this point a big challenge is how to move cold coils inside cryostats.

In the SEA-TITAN project, the conceptual design of a Superconducting PTO was based on two considerations:

→ It must be simple and robust within the constraints imposed by the limitations of operating at cryogenic temperatures.

→ All the machine windings (ac and dc) must be superconducting in order to increase the efficiency and to reduce the weight.

The proposed superconducting switched reluctance machine has coils only in one side, the stationary one. In this way the superconducting coils do not move, simplifying enormously the execution of the machine.

ASG Superconductors Contribution

ASG, thanks to the experience in superconductivity and wire production, is one of the partners of the Sea-Titan project, especially for the work package related to the development of a superconducting PTO.
Two Business Units have been involved in this project: the Columbus MgB_2 Unit and the Magnets & Systems Unit.

MgB_2 is the best material for a superconducting PTO thanks to its relatively low operational magnetic field. It can carry high currents without needing to be maintained at liquid helium temperature, reducing the cooling power. Moreover, thanks to the stability and the relatively high Tc of the material, the need for maintenance of the cryogenic systems is reduced, along with operating costs.

With the greater flexibility of the unique MgB2 wire ex-situ process, Columbus MgB_2 Unit has succeeded in designing and developing improved solutions for products ranging from power cables to magnets for the medical and energy sectors. The manufacturing process provides MgB_2 wires with the electrical performance, mechanical properties and single piece lengths required to allow the use of react & wind technology. This minimizes the number of joints and brings HTS device manufacture one step closer to the well-established NbTi technology, while keeping the advantage of the higher operating temperature.
Within the Sea-Titan project, the Columbus MgB_2 Unit was appointed to define and optimize the wire for the superconducting coils in the PTO. In order to reach this goal, its experience in MgB_2 wire fabrication has been fundamental.
The most suitable wire for this application is a standard production round wire usually made for high-current transport purposes. The wire has a round shape with an overall diameter of ~1mm and a multifilamentary architecture comprising 37 monofilaments. The wire is made using a standard undoped MgB_2 powder providing optimized performance at low magnetic field and high temperature. More than a million metres of wire have now been produced and the required operating characteristics can be achieved and maintained homogeneously over a length which is nowadays > 3500m (single piece).

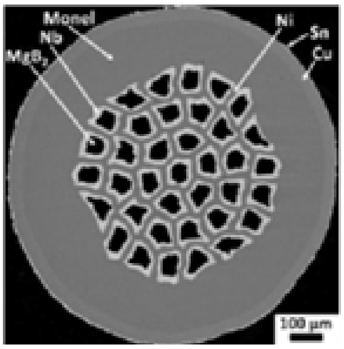

Figure 8 MgB_2 round wire.

The Magnets & Systems Unit has acquired industry-leading know-how in the design, development, production, installation and testing of superconductive and resistive magnets, cryogenic systems, resonance cavities, superconducting solenoids and coils, magnets for cyclotrons and components for made-to-measure applications.
The Unit has been involved in the Sea-Titan project with the goal of handling the ac losses. Thanks to its experience it has had the right skills to face this critical aspect of the design of a superconducting PTO.

Perspectives

Diversifying the available sources of renewable energy is crucial to achieving a climate neutral EU by 2050. Wave energy converters are expected to contribute to this goal, but significant R&D is still needed to identify the best technical solutions to achieve high power conversion efficiency and a reasonable cost per kW. Superconductivity will play a role, provided that low ac loss conductors and winding solutions would be applicable. The Sea-Titan project outcomes will contribute to clarifying these aspects and helping wave energy to approach these targets.