SEA-TITAN: A FIRST STEP TOWARDS THE SUPERCONDUCTING WAVE ENERGY PRODUCTION

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By 2050 the 10% of Europe's electricity demand would be produced by ocean energy (100 GW of ocean energy capacity – 350 TWh of electricity).

The ocean energy is based on the use of Wave Energy Converters which produce energy from waves. The core of a WEC is the power Take-Off, which transforms mechanical movements into electrical energy.

Superconductivity can help to meet the energetic goals enhancing the power generated by electrical machines without increasing volumes.
The best choice is to work with a high temperature superconductor as MgB_2: thanks to the stability and the relative high Tc of the material , maintenance costs and efforts could be significantly reduced.

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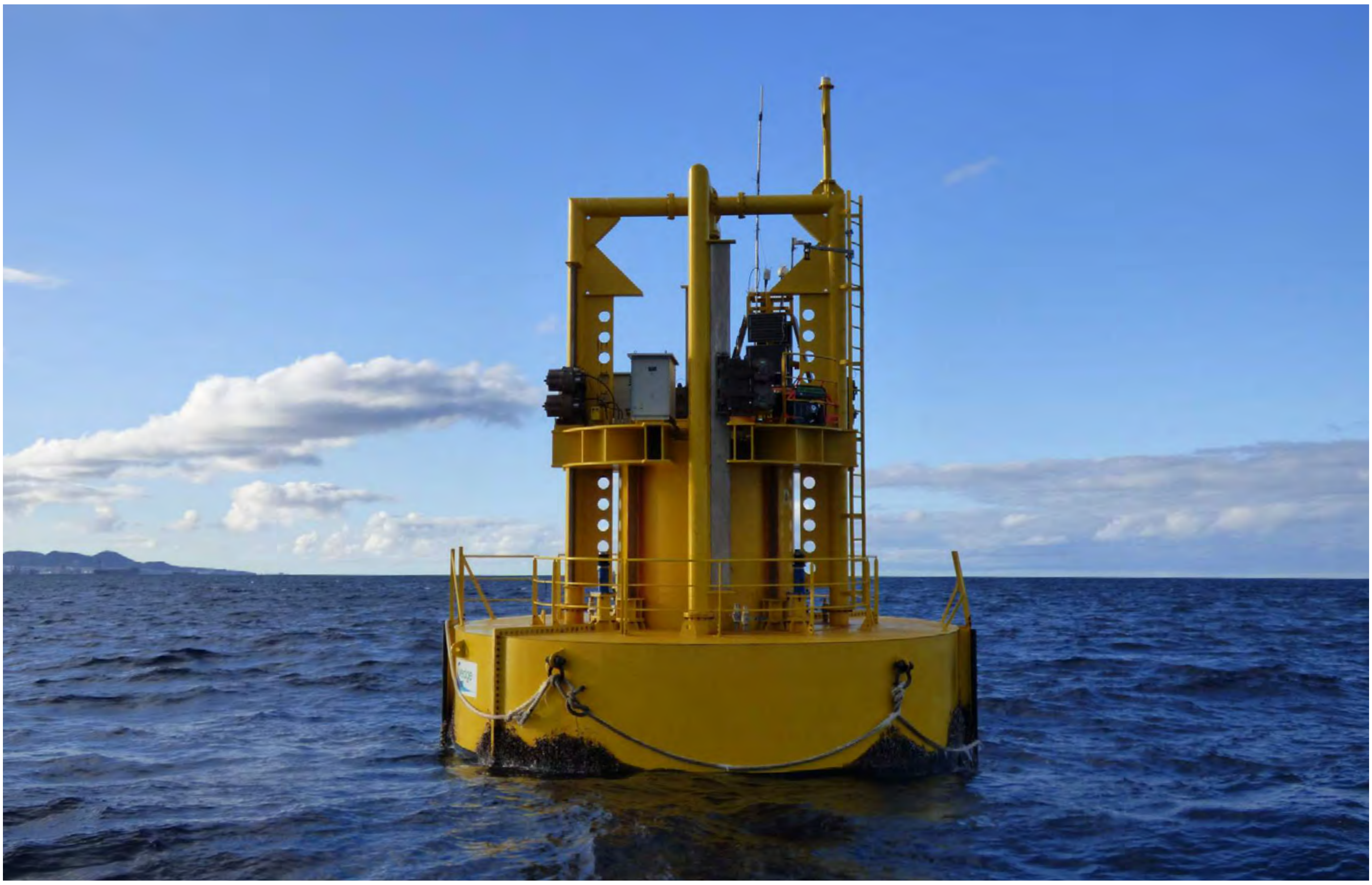

Introduction

Europe's 2050 Energy Strategy has established a target to reduce greenhouse gas emissions by 80%-95% compared to 1990 levels and renewable energy accounting for at least 64% and up to 97% of the electricity consumed.
In particular, ocean energy could sustain up to 10% of Europe's demand by 2050. The Ocean Energy Strategic Roadmap has estimated that 100GW of ocean energy could be deployed in Europe by 2050, producing around 350TWh of electricity.
Superconductivity can help to meet the energetic goals enhancing the power generated by electrical machines without increasing volumes.
Nowadays different alternatives to develop superconducting machines have been proposed, basically in the sector of wind energy, where several rotary generators have been developed in order, basically, to alleviate the weight and to increase the efficiency.
Two critical points can get difficult the realization of a superconducting machine: how to keep cold the coils (temperature lower than 50 K) and how to reduce ac losses.
The first problem can be solved considering a switched reluctance machine: this machine requests coils in only one side, the stationary one. This fact simplifies enormously the design of the machine.
Ac losses are a wasted power that is generated in a superconductor when it is in a magnetic field varying in time. These losses produce heat that must be extracted increasing the complexity of the facility. Since they depend on the field variation with the time, they are very sensitive to the frequency. This fact implies that for standard commercial frequencies (50 Hz), ac losses are simply inadmissible with the present status of the technology. For this reason, most of the superconducting electrical machines use superconductivity only on the dc side. Nevertheless, the interest of finding solutions for using superconductivity also in the ac side of the machine is increasing, since it would represent a big reduction in the sizes and efficiency of the machine.
Implementing a superconductive solution in the ocean energy conversion process is one of the goals of the SeaTitan project. In particular, it had the purpose to study the possibility to implement a superconducting linear machine that could work in ac.
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.
Thanks to its expertise, ASG was involved in this project; in particular in the definition of the wire and in the estimation of ac losses.

Power Take-Off: the core of the ocean energy conversion

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 the mechanical movement of the waves in electrical energy.
Several configurations of PTO exixts, the SeaTitan project focused its work on the so-called Direct-Drive System.
All the Direct-Drive machines are based on a Translator/Stator configuration that balances transverse forces.
The force in ocean energy is given by waves. In order to maximize the energy production, the system must work close to the resonance.
In this configuration, the Stroke, the maximum amplitude of the translator motion, can be high even if the waves are small.

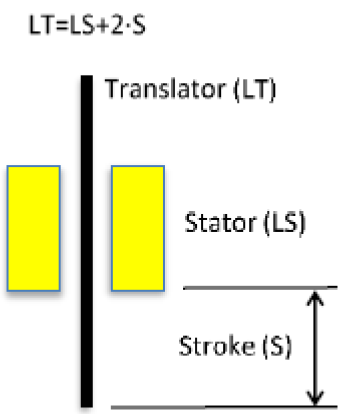

Figure 1 Direct-Drive machine scheme.

Any electrical machine is defined by the Shear Stress, the force produced by 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).
In general, this magnetic field can be generated by permanent magnets or coils. In marine applications, permanent magnets are not appropriate because they are very delicate components, prone to corrosion. In this case the coils can be resistive or superconducting.
The core of the Sea-Titan project is to develop a new PTO. One way to achieve this goal is based on using superconducting coils.
In particular, the Sea-Titan project tried to convert a resistive PTO, based on a Switched Reluctance Machine (SRM), in a superconducting one.
In this kind of electrical machine there are an Active side (coils generating the magnetic field) and a Passive side (iron); only one of the side is moving.

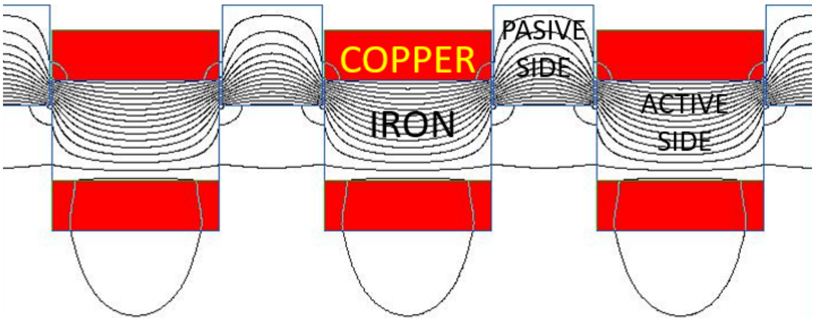

Figure 2 A Switched Reluctance Machine has an Active side (copper and iron pole) and a Passive side (iron) moving one respect of the other.

While in the resitive configuration the moving side is the Active one, in the superconducting study the coils are designed to be fixed and the iron is moving. In this way the problem related to the cooling of a moving component is solved. As previously reported, to enhance the efficiency of an electrical machine it is necessary to increase the product between the current and the magnetic field density.
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 (little bigger for the superconducting one), this small variation in the field (in the range of 10% to 20%) implies a tremendous variation of the current and consequently on the force.

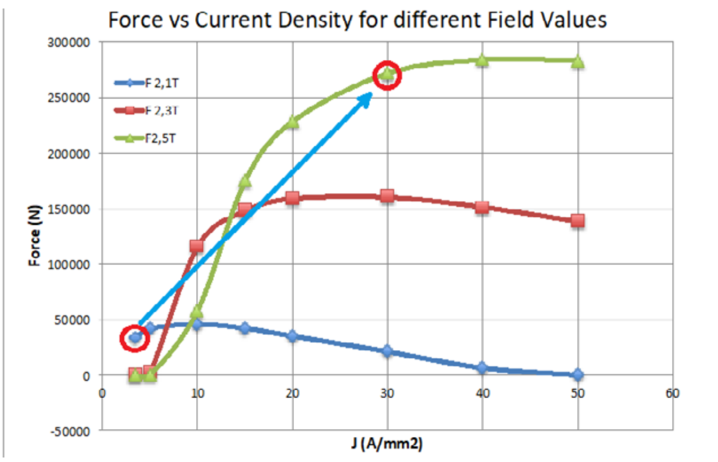

Figure 3 Force vs Current Density for 3 values of B. For a normal conductor, working above 3-4 A/mm^2 is not possible (the best option is the blue curve). For a superconducting machine it is possible to achieve 30 A/mm^2, jumping to the green curve.

A superconducting PTO: the wire definition

Since the goal of this kind of machines is to generate power, it is basic to reduce the power necessary to keep cold the system. In order to reach this goal, the best choice is to work with a high temperature superconductor as MgB_2.

Magnesium diboride, MgB_2, has been regarded as a very promising candidate for alternatively commercial superconducting materials since the discovery of its superconductive properties in 2001. Together with its simple crystalline structure and low material cost, the transition temperature around 40 K enabling a cryogen-free operation is definitely attractive for engineering applications allowing to drastically decrease capex and opex with respect to superconductors which need liquid refrigeration fluids.

Superconducting PTOs and, in general, superconducting machines as well as cables for current transport represent ideal application for this material, thanks to their relatively low operational magnetic field. Moreover, thanks to the stability and the relatively high Tc of the material, maintenance costs and efforts could be significantly reduced.

ASG, in its Columbus Wire BU, has been involved in the Sea-Titan project thanks to its expertise in the production of MgB_2 wires. The MgB_2 wire fabrication starts using ˜ a Powder-in Tube (PIT), ex-situ approach, allowing a better control over powder performances with respect to an *in-situ* approach.

Powder is inserted into a metal tube, which then is cold-worked by drawing. This tube, called "monofilament", is the base unit for multifilamentary wires which are made of multiple monofilaments, stacked together inside a larger metal tube and then deformed to produce a wire.

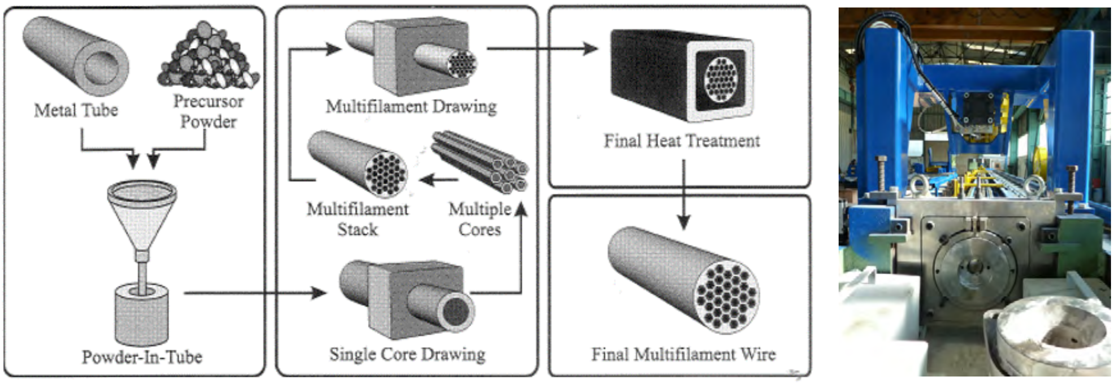

Figure 4 MgB_2 wire manufacturing process.

The full in-house-developed process is able to realize an elongation factor of 2000, having as a result kilometres of continue and uniform spools.
The process ends with the final heat treatment, where the wire is given its final superconducting and mechanical properties.
Wire architecture, materials and heat treatment are carefully selected to meet the magnet design and requirements, in a cost and quality driven approach. Besides the actual portfolio of standard product, custom wire shall be designed to cover specific needing.
One of the suitable wires for the application is a standard production round wire usually made for high-current transport purposes. The wire has a round shape having ~1mm of overall diameter and a multifilamentary architecture made of 37 monofilaments. The powder is a standard undoped MgB_2 with optimized performance at low magnetic field and high temperature. After more than 1Mm of total wire length production, requisites are met and homogeneous over a length which is nowadays > 3500m (single piece).

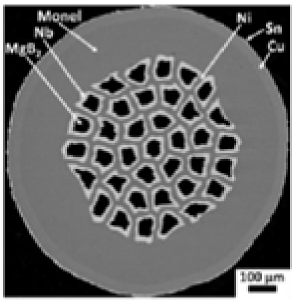

Figure 5 MgB_2 round wire.

Material	Composition [%]
MgB2	12
Nb	13
Ni	15
Monel	46
Cu	14

A superconducting PTO: 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 for Joule's effect (described by the following equation)

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

This is true if the coil is powered by a dc current. If a superconductor sees a field variation with the time, as in an a.c current situation, a wasted power is generated inside the superconductor. This power warms the coils, so a higher cooling power is required to keep the coils cold.
Since the electrical machine needs to generate power, a positive balance between generated and used power is necessary.
ASG, in its Magnet BU, was involved in the Sea-Titan project to study how the ac losses affect the superconducting PTO behaviour and to find how to reduce their impact.
Superconductors subjected to varying magnetic fields see multiple heat sources that can impact on the conductor performance and stability.
The first heat source is called Hysteretic loss and it is due to the magnetization cycle of the superconductor. This kind of loss is proportional to the the magnetic field variation rate and to the wire properties (number and diameter of filaments and critical current). If the wire transports current, the loss is enhanced.
The second kind of loss is present only in multifilamentary wires and it is due to the intrafilamentary currents. It is possible to demonstrate that a superconducting wire subjected to an external varying magnetic field induces an electrical field, and consequently a current in to the resistive wire stabilisation matrix. These losses are called Coupling Losses and they are proportional to the magnetic field variation rate and to the matrix electrical conductivity.
Lastly, if in the conductor there are ferromagnetic materials, another kind of Hysteresis Losses can develop inside these materials. The calculation of this component is always related to the area of the ferromagnetic material magnetization cycle.
ASG, in its study, implemented Wilson's formulation for ac losses in a Matlab code. Considering the temporal magnetic field trend on each single wire inside the coil, the ac losses generated on each wire were calculated. This study showed that the main loss factor in the superconducting PTO is due the Coupling Losses. The low resistivity of the stabilizer matrix and the high magnetic field variation rate generate high Coupling Losses. In order to reduce this dissipation, it is necessary to act on both the wire characterization and on the profile of the current flowing inside the coils.
These results could be the starting point for another project.

Conclusions

Superconductivity could give a great improvement to the power generation. Nowadays some superconducting solutions have been implemented in wind energy, but also the ocean energy could be interested in a superconducting conversion.
The Sea-Titan project has started to work in this direction. A goal of the project was the feasibility study for a superconducting Power Take-Off. ASG had a main role within this specific target thanks to its expertise. Two topics were in charge of ASG: the MgB_2 wire definition and the study of ac losses.
The result of the study showed that the ac losses could be a critical point because they are too high. Other studies are necessary to implement a superconducting solution for the ocean energy production but they are an investment for the future.