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The MARES Project: Development of a New Power Take-Off based on a Superconducting Switched Reluctance Machine

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The MARES Project: Development of a New Power Take-Off based on a Superconducting Switched Reluctance Machine

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Abstract—**In spite the problems that some of the wave energy converters projects have suffered in the past, the need and convenience for extracting energy from the sea waves is still strong, mainly due to the requirements that the blue economy is demanding. Heave point absorbers in their different versions are a very interesting option for converting wave energy into electricity and several technologists have adopted it in different configurations for producing electricity. In any case and for a given wave energy converter, extending the region of wave periods where the extractable amount of energy is still considerable, extremely forceful and efficient PTOS are required and this provides a convenient opportunity to the superconductivity, since the required high force is associated to the high current superconductors can transport, while the required high efficiency is associated to the absence of Joule losses.**

Based on these statements a group of partners has elaborated a proposal for developing a new concept of superconducting PTO based on a Switched Reluctance Superconducting Machine and a Flexible Cryostat that confines all the different parts of the electrical machine, avoiding moving elements passing through the cryostat.

This proposal, the so-called MARES Project, has been submitted to the HORIZON-CL5-2024-D3-01-10 European call and finally granted with the main goal of developing a prototype based on two different technologies of superconductors and also to explore its implementation in two real Wave Energy Converters which were previously developed by two of the MARES Project partners.

Keywords—**Superconducting, Reciprocating PTO, Wave Energy Conversion, Switched, Reluctance, Machine**

I. INTRODUCTION

In a report published in 2021 by the Bank of America Global Research entitled "To the Moonshots: Future Tech Primer" [1], 14 Technologies (the moonshots) for the future were listed and analyzed. One item of this list is Oceantech, including harvesting the ocean energies to also produce electricity. The report forecasted that by 2030 the ocean global economy (obviously including much more aspects than solely energy production) will be equivalent to 2010 Germany GDP, existing a general consensus on the tremendous impact and activity that it may induce in ocean energy generation, including that required for activities associated to the blue economy.

The electric power that can be converted from an ocean planar wave is proportional to the wave period and to the square of the wave amplitude but, to extract the maximum available power from the waves, the system must be able to be tuned, which means having the availability of producing high reactive forces (proportional to its displacement or to its acceleration) which can be even higher than the required active force for producing energy. Consequently, Power Take-Offs (PTO) have always been

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at the focus of the research, development and innovation in the wave energy sector and they have been one of the main priorities for wave energy during the last years. As a result, the European Commission has funded several projects in recent years [2], addressing its development and optimization under the Horizon 2020 calls, such as OPERA, WaveBoost, WETFEET, IMAGINE and SEA TITAN.

MARES is a recently granted Horizon project proposing the development of a novel concept for a PTO able to produce the required big forces very efficiently, in a reduced volume (high force density) and disregarding permanent magnets-based solutions requiring enormous quantities of rare-earth materials. The use of a simple generator topologies (such as a cylindrical switched reluctance machine) and novel superconductors such as HTS or MgB_2 make the proposal even more attractive, not only for wave energy conversion but also for other applications where very high force densities are required.

This paper will first introduce the MARES Project to describe next, the conceptual design of the superconducting generator prototype, a machine that will include both technologies of new superconductors and that will be also fabricated and tested by the MARES consortium. The Project also includes the implementation analysis of this PTO concept into two real cases of Wave Energy Converters.

II. THE MARES PROJECT OBJECTIVES

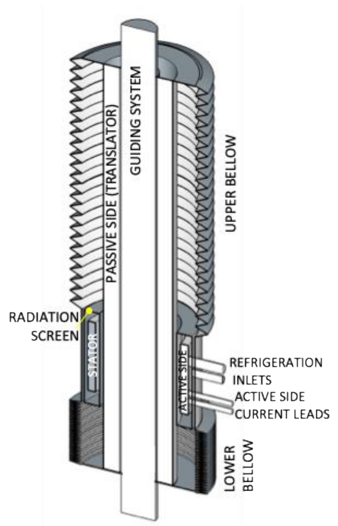
The project mission is to go one step beyond the present State of the Art in direct-drive PTO technology by introducing superconductivity as an enabling technology to achieve a significant increasing of the specific force and also an improvement of the overall efficiency. Specifically, the global objectives stated in the MARES proposal can be listed as follows:

1) **Developing a concept PTO based on innovative Reciprocating Superconducting Generator (RSG)** and its associated Power Converter, and Cryogenic Systems**:** Investigating the concept of a new RSG and proving its feasibility by designing, fabricating, and testing a conceptual prototype to be fully characterized at the Lab (TRL 4).

2) **Reducing development time and lifecycle risk of wave energy converters:** Exploring the adaptability of this generator to two specific developments for Wave Energy Converters from two experienced WEC technologists, for which an ocean test rig was developed.

3) **Improving EU competitiveness in Wave Energy Conversion, targeting at contributing to an overall significant reduction of the LCOE, a reduction of contaminating materials while increasing the circularity and reusability of the components.** Economic and environmental assessment on the integration of novel RSG in two WECs: UNDIGEN [3] and SYMPHONY [4]**.**

MARES aims at developing a next generation of ultrahigh force Superconducting PTOs based on a **Reciprocating Superconducting Generator (RSG)** which is simpler than other existing superconducting generators. Its alternating (reciprocating) movement allows the direct integration into wave energy converters where the prime energy source is also moving in the same way. This RSG consists of a **Cylindrical Switched Reluctance Machine** [5] **with Superconducting Coils** housed inside a **flexible moving cryostat**, avoiding the need of any feedthrough in the moving parts (feedthroughs are only needed at the stationary side). The machine is cooled down using a novel Cryogenic Supply System (CSS) which recirculates helium gas through the coils and thorough the radiation screen & current leads at two different temperatures [6]. One of the two sets of the generator coils will be made from MgB_2 superconducting technology, while the other one will use REBCO tapes and the achieved results for different working temperatures will be assessed and compared. In both cases the proposed technology will profit from the latest advances in superconductivity and cryogenics and very specifically in recent developments in superconducting magnet technology provided by six of the participants, including the European Organization for Nuclear Research (CERN) a world leader in such activities, The RSG will be completed with a new Control and Powering System according to its singularities to configure a fully innovative PTO [7].



SOME Figure 1. The RSG Concept JCCESS

KPI	Value
Developed Force	> 1kN
Max. Stroke	± 0.5 m
Max. Speed	1m/s
Force Density	> 100 kN/kg
Efficiency	> 95% (Cryogenics excluded)
Testing Hours	> 50 h

Figure 1 shows the global concept of the Reciprocating Superconducting Generator which will be described later on in more detail.

Basically, it consists of a Cylindrical Switched Reluctance Machine (a well-known and extended concept in the non-superconducting version) [8] whose windings are either High Temperature Superconducting (HTS) tapes or MgB_2 wires constituting the stator of the machine. For the moving part (the translator) no windings are required and only laminated iron is needed. Both, the translator and the stator are housed inside a flexible cryostat avoiding the use of vacuum joints with a moving shaft. The stator is cooled down circulating gas helium which is provided by a Cryogenic Supply System which is a closed loop helium circuit which cools down the heated gas in the stator using a cryocooler [9].

Table 1 lists some measures of Project success in terms of KPIs (Key Performance Indicators)

III. THE MARES PROJECT PROGRESS & IMPACT

The use of superconducting machines (SC) and other superconducting devices in applications related to renewable energy generation and transmission has been proposed and developed during the last years [10]. The advent of two new related enabling technologies like the MgB_2 and HTS cuprates based superconducting wires and tapes has renewed the interest in such devices for those applications, since their performances with respect to previous technologies (NbTi or Nb_3Sn) can improve significantly, especially regarding the increasing in the operational temperature with the corresponding technological simplification.

Nevertheless, the existing background is concentrated on rotating machines for wind energy generation. Wave energy generation, as far as the authors know, is still a field hardly explored for superconducting PTO technologies.

They are all based on synchronous generators with either one or two active sides [11]. While some developers advocate for single superconducting machines in which only the DC side is superconducting, other propose fully superconducting generators in which both sides are superconducting. In any case two big problems may arise. The first affects both solutions and is how to feed and cool down windings which are rotating and the second one, only affects fully superconducting generators and is the generation of AC losses in the superconducting windings of the static side. The solution lays on a complex rotating cryostat with either static refrigeration and rotary seals or with rotating refrigeration based on cryocoolers moving together with the cryostat [12].

The second problem only affects fully SC generators and is the generation of AC losses in the SC windings of the AC side. The solutions for it concentrates on the development of suitable conductors with a high resistive matrix, a low filament size and a short twist pitch, Table II summarizes the main issues related with SC rotary machines in their application for wind turbines which can be augmented by the fact that the machine is operating in a relatively harsh environment and must be placed and operated in a difficult access location.

Although its demonstration is out of the scope of this section, the force that a PTO must produce (curve A, in Figure 2.b) to harvest the maximum theoretical power (curve C) can be very high for wave periods far from natural resonance [13]. When using a conventional PTO with a force limit and a non-ideal 100% efficiency, the amount of produced power is reduced enormously from the ideal value (Curve G shows the maximum achievable power in an existing buoy with the conventional PTO that it houses, with a force limit of 150 kN and an efficiency of 75%). Using an ideal PTO with a 100% efficiency and a force limit of 1000 kN would lead to produce the power represented by curve (D) requiring the force in curve B. Achieving this ideal value (or close to it) would only be possible by using a Superconducting PTO (Sc PTO) able to produce such big forces with a generator of equivalent sizes to a conventional one. The price to pay for this capability is the complexity of the required solutions to refrigerate the moving coils of the generator which is placed in the ocean.

TABLE II
ISSUES RELATED WITH SC ROTARY GENERATORS

Requirement	Associated Issue	Solution
Rotating DC SC Coils	Cooling the moving coils	Current Leads with Slip Rings
	Powering the moving coils	Rotating Cryostats connected to a stationary cooling system
		Rotating Cryostats with rotary Cryocoolers
SC AC Stator	High AC Losses	Coil design to cancel the perpendicular field to the tape, small filament, twist pitch, matrix metal

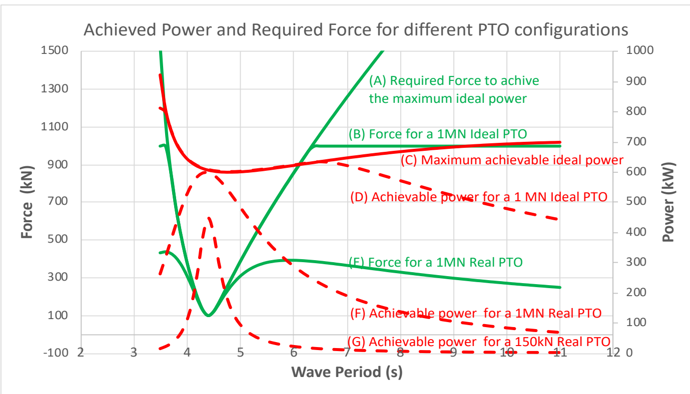


Figure 2. Ideal & Real Power and forces in a Point Absorber

There are many different systems based on the heave point absorber concept. Of especial interest are those developed by two of the partners of this proposal. The one from TEAMWORK (the SYMPHONY system) (see figure 3) was developed in the framework of another EU project (the ENCORE Project [14]). The system is fully submerged; the spar is the central leg which is anchored to the seabed and the float is the buoy which is also oscillating up and down with respect to the leg. A tank full of nitrogen at a controllable pressure, acts as a spring to drive the system to resonance.
The transferring of the fluid from a reservoir to the tank moves a turbine which drives a generator to produce electricity.

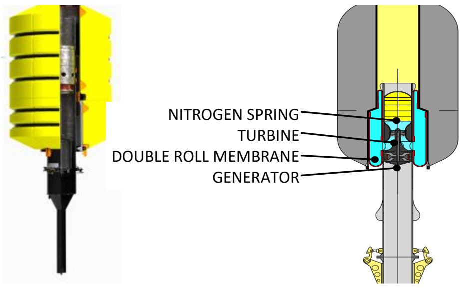


Figure 3. The Symphony Wace Energy Converter proposed by TEAMWORK, a partner of MARES

The other system is the one developed by WEDGE GLOBAL (another partner of the MARES project) which is called UNDIGEN [15]. It is basically a float moving up and down along a spar (see figure 4). The float is connected to the translator of a linear generator, while the spar is connected to the stator. The relative movement between both, generates electric power in the linear machine.

Figure 4. The UNDIGEN Wave Energy Converter proposed by WEDGE GLOBAL a partner of MARES

IV. THE MARES PROJECT: AN ALTERNATIVE BEYOND THE STATE OF THE ART

The summary of the situation described previously is that there is a need for making compact PTOs using generators with a high-power density at an affordable cost and limited complexity. This need was clearly detected for the case of offshore wind and materialized in different designs and realizations of SC rotating generators. All these developments are based on superconducting **coils** which must be placed inside a moving cryostat. Table II has shown the issues related to this configuration and how they are addressed but, in any case the solutions to the problems are quite complex.
To better understand the concept underlying this solution, it is very convenient to review each of the three different configurations that may be adopted for SC (Super-Conducting) linear machines with only one active side, which are depicted in Figure 5a and Figure 5b [9].
Obviously, there is one main condition to fulfil: **SC coils must be at cryogenic temperature**; the rest can be either at cold or warm temperatures. Figure 5.a represents a configuration where only the SC coils are cold and figure 5.b another one with a fully cold stator (iron and coils) and a warm translator.

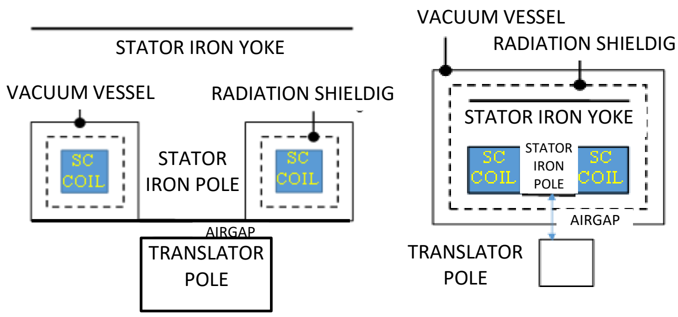


Figure 5.a Machine configuration where only the coil is cold.5.b Coils and iron stator are both at cold.

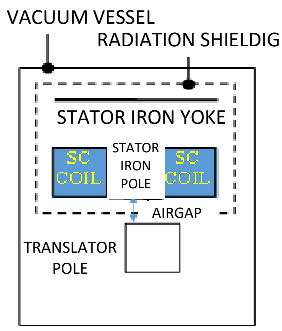


Figure 6 Machine configuration where both, Stator and Translator are cold

The biggest difference between them concerns the airgap size: in the first case it can be similar to conventional non-superconducting machines (i.e. in the order of 1 mm); in the second one, there is a limitation to the airgap which must be bigger than the width of the cryostat (in the order of 50 mm considering the required separation between the coil and the wall and also the presence of a radiation screen). Apparently, the first case should be preferable to the second one since the airgap is much smaller, but there is a big issue associated to it: since each coil requires its own cryostat, the equivalent coil size (including the coil and the cryostat) can be of the same order of magnitude as for a conventional non-superconducting coil.

Additionally, the mechanical support of the coil becomes very complex in order to hold the big electromagnetic forces that are produced.

For the case of a reciprocating machine, there is a third option, to cool down both sides of the machine, stator and translator, leading to a reasonably small airgap only conditioned by the presence of the radiation screen. Based on the third solution, we have developed a **proposal for a superconducting linear-displacement generator (Reciprocating Generator)** as shown in figure 7. The complete machine is allocated inside a flexible cryostat, formed by two upper and lower bellows (2) & (7) attached to a central stationary body (6). The latter houses the stator (5) with the superconducting coils and the surrounding radiation screen (4). On its side, the translator (3) is fixed to the moving parts of the cryostat, but it is thermally insulated from them. This solution should be considered as a reciprocating machine with a limited stroke, rather than a conventional linear machine with no limitation to its displacement. This proposal constitutes a completely novel approach and as far as the authors know, there are no previous related realizations. In fact, the idea has been granted with a national patent [16].

The previous concepts are applicable to different types of superconducting electrical machines. The two basic choices to perform are: 1) the type of electrical machine and 2) the choice of the superconducting material.

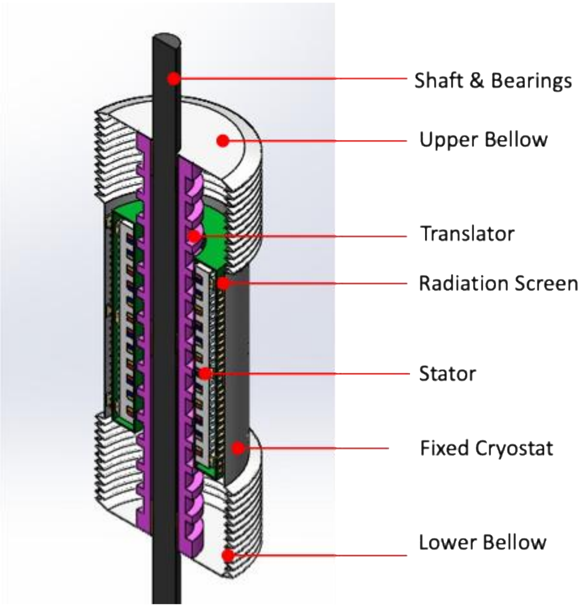


Figure 7 Main Components of the MARES Generator

To answer the first question, the main driving arguments are robustness, simplicity, and cost. In this sense, two partners (CIEMAT and WEDGE) have plenty of experience in the development of Switched Reluctance Machines (SRM) for applications in Wave Energy, Kinetic Energy Storage, Electric Vehicle Propulsion, and others, which are also driven by similar arguments. The SRM is simple, robust, and cheap because its moving part is simply a piece of laminated magnetic steel, coils are flat, and they can be wound very easily using the double-pancake technique.

These characteristics are especially adequate to also provide modularity to the machine. It is true that its electromechanical simplicity must be compensated with a more sophisticated control than what is required for other types of electrical machines to achieve similar performances, but sophisticating the control is always easier and cheaper than the electromechanical parts. Within the generic category of SRM machine there are different configurations. For our application, there are two severe limitations: **a)** the separation between the stator and the translator (airgap) in where a non-metallic radiation screen must be placed and **b)** the maximum bending radius of the coils allowed by the superconductor. Said this, we concluded that the best topology is a Cylindrical SRM (CSRM) as sketched in figure 8, which represents one of the possible configurations in terms of stator poles arrangement [8]. They are simple machines and also less problematic from the point of view of the small curvature radius existing in other type of coils such as racetrack coils, used in other configurations of SRM machines.

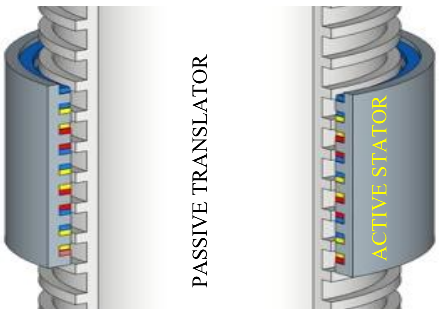


Figure 8 Configuration of the CSRM

Concerning the superconducting material to use, we have selected two options arising from the background and experience of the participants in other related realizations and also from the required magnetic field value for this specific application (in the range of 2-3T). On the one hand, we propose MgB_2 (Magnesium Diboride) and on the other ReBC0 tapes (Rare earth Barium Copper Oxide). MgB_2 belongs to the group of BCS type superconductor with the highest critical temperature of all superconductors in that group. Its main advantages are: lower price (≈20 €/kAm @ 20K) and the ability of being produced in long lengths of filamentary wires in order to reduce time varying field losses (ac losses). On the disadvantages side it needs to be reacted after winding, in some cases, and its electrical transport properties are more modest than for the other candidate. To achieve the required current for operation, it is necessary to work below 20K-25K. ReBCO tapes, on the contrary, present better transport properties at similar temperatures keeping fairly good properties at much higher temperatures [17]. On the negative side, their price is higher (in the range of 40 €/kAm @ 20 K and 140€/kAm @

50 K), they cann´t be produced in long lenghts and their ac loses are also higher since they cann´t be made in a multifilamentary arrangement.

The suitability of these materials for this application can be better understood with the help of figure 9, representing the product of critical magnetic field density B, times critical current density J for different B values at different temperatures. This product is proportional to the maximum force density (N/m^3) that the machine is able to produce and here is where superconductivity becomes a fully disruptive technology. In the same graph there are also included values of B·J for copper used in standard machines at 4 A/mm^{-2} (which hardly work beyond 1.5 - 2.0 T). Three things are relevant: a) Maximum values of B·J are achieved in the range of B values required for this application, which includes iron in the main magnetic circuit b) Force densities for our proposal can be from one to two orders of magnitude higher than those for conventional machines at significantly high temperatures in the cryogenic environment. Although not presented, MgB_2 presents even better values, but it needs to operate at a much lower temperature (in the range of 20K).

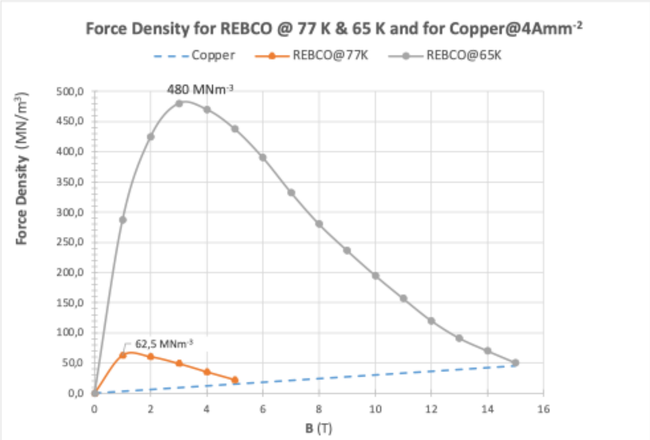


Figure 9. B·J product for REBCO and Copper at various temperatures

The MARES consortium has experience with both materials: ASG [18] is one of the world´s most important MgB_2 manufacturers and has participated in many different projects using this type of superconductor like the development of an open magnetic resonance device, the superconducting links for the HL-LHC project at CERN, the contribution to the SUPRAPOWER Project in which also SUPRASYS and CIEMAT (inderectely) participated, the V-ACCESS in which ASG is marinizing an MgB_2 SMES or the contribution to the SEA TITAN [19] project in the design phase of the reciprocating generator that we are proposing to develop now. Regarding ReBCO, CYCLOMED, ANTEC, CIEMAT, CERN, and EFESTO are now involved in the POSEIDON [20] project in which one of the activities is to develop a Superconducting Magnetic Energy Storage System for Marine Applications based on ReBCO tapes. ANTEC and SUPRASYS have participated in the HIVOMOT project for developing a HTS-based aircraft motor . Besides, all these partners have a long track record in Superconductivity and particularly in HTS. Worth to mention CERN as the world´s reference in superconducting magnets. Probably, one of the most important technical results of the MARES project [21] will be to asses both superconducting technologies for this application and to define and optimize their operating conditions. Generally speaking, and compared to other superconducting machines, these are the main features:

1) **Only one superconducting and stationary active side**: A SC moving winding implies a much more complicated cooling system that must either rotate or be connected through low temperature seals.

2) **Simple and robust iron translator with no windings**: In a SRM the moving part is simply iron. It is truth that this limits the maximum achievable magnetic field to the saturation field of the iron, but this could represent an advantage for MgB_2 and ReBCO, able to work very comfortably at those fields with an enormous current carrying capacity. The consequence is that the force density of the machine can easily be augmented by a factor of 10-20 compared to a non-superconducting machine.

3) **Fully closed cryostat which completely houses both sides of the machine**: The machine is allocated in a closed enclosure and no additional parts need to come out or in from it, except the stationary cooling inlets and the current feedthroughs which are mandatory for any type of solution.

4) **A relatively small airgap can be achieved** which means that the required ampere-turns are reduced and, in any case, are much smaller than for solutions based on two superconducting sides, each in its own cryostat.

5) **Coils are refrigerated with gas**: Unlike other solutions which are based on conduction cooling refrigeration schemes where heat extraction becomes very difficult for places far from the thermal connection points, our systems guarantee access and a similar cooling capacity for every point in the coils.

In any case, there is no need to say that a superconducting machine is more complicated than a conventional one, but the expected results are worth to be explored since other applications of superconductivity in the marine environment have shown to be feasible. On the other hand, the present and frenetic activity in developing new superconducting materials able to show superconducting properties at much higher temperatures constitutes an incentive for working on superconducting generators that will tend to become simpler and more reliable in the future.

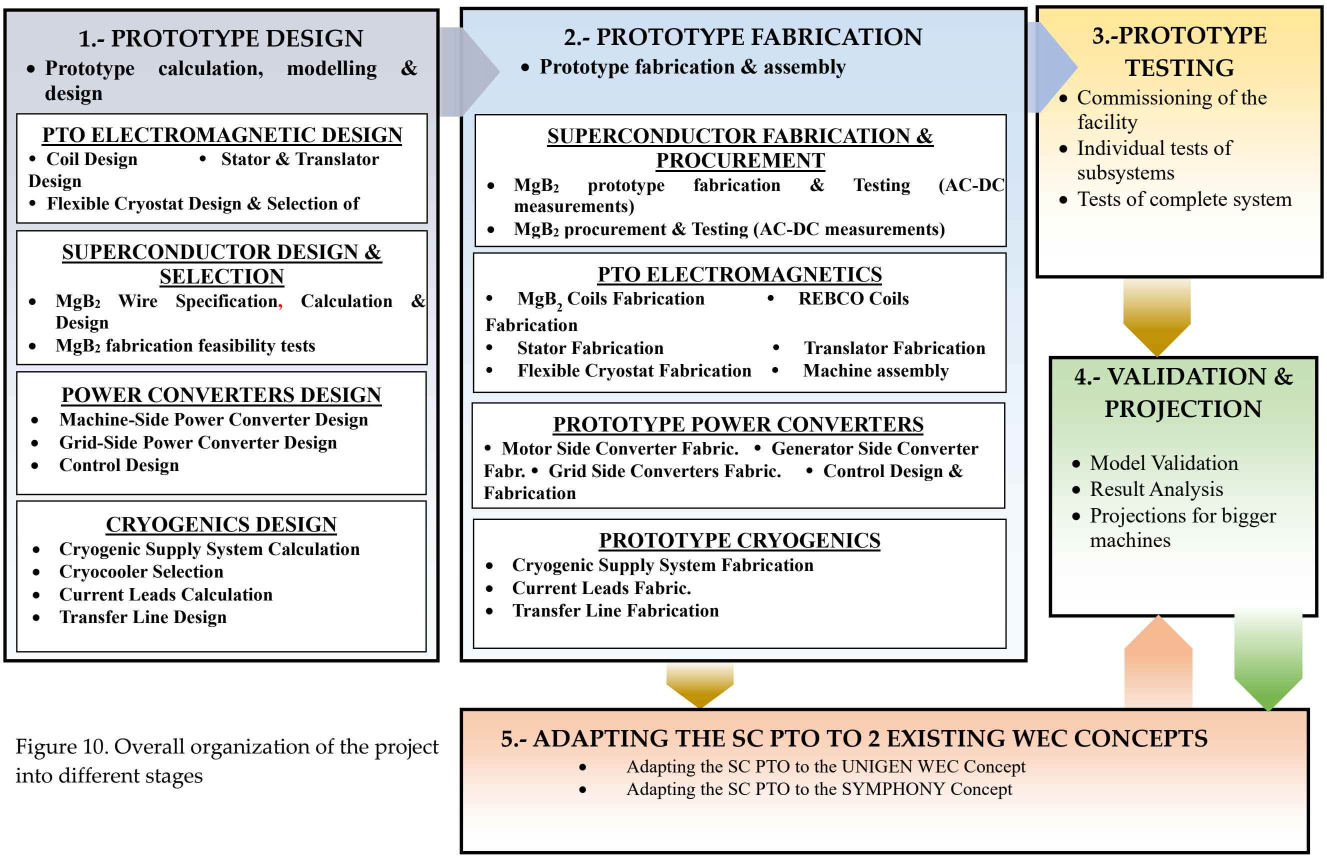


Figure 10. Overall organization of the project into different stages

V. THE MARES PROJECT METHODOLOGY

The development of MARES is based on the workflow depicted in Figure 10 with several group of activities clearly associated to the achievement of the objectives. These stages generate the corresponding work packages. The core activity of the project is to develop a complete PTO unit to validate the idea and, specially, both superconducting technologies. Presently, the project is fully immersed in the Work Package 1(according to figure 10 , where the calculation and conceptual design of the machine and other subsystems must be afforded.

For the specific case of the machine, a simplified model (the Mares Model One-MMO) has been developed and run and lately checked with more precise FEM codes. Global accuracy of MMO is fairly good, although the peak field value determination (a critical value for superconducting machines) needs to be improved. The model is based on the simplification of substituting the Maxwell and Lorentz Forces existing in the real machine with solely Lorentz forces in an ideal machine where all the ampere-turns are located along two thin conductors placed in the airgap, creating the same field distribution in that region. In the real machine, magnetic field lines crossing the coils (in red in figure 11.a) produce Lorentz forces in the direction of the movement, while magnetic lateral field lines leaving the iron in the same direction, produce Maxwell forces. In the simplified model (figure 11.b) there are only transversal Lorentz forces in the conductors (in red) since there are no magnetic field lines leaving the iron in the direction of movement.

AC and Iron Losses have also been calculated based on classical equations that provide rough estimates which allow performing the first dimensioning of the machine. Presently, much more sophisticated models using COMSOL and other tools are under development with the goal of improving the calculations of such critical losses and other tools are under development with the goal of improving the calculations of such critical losses.

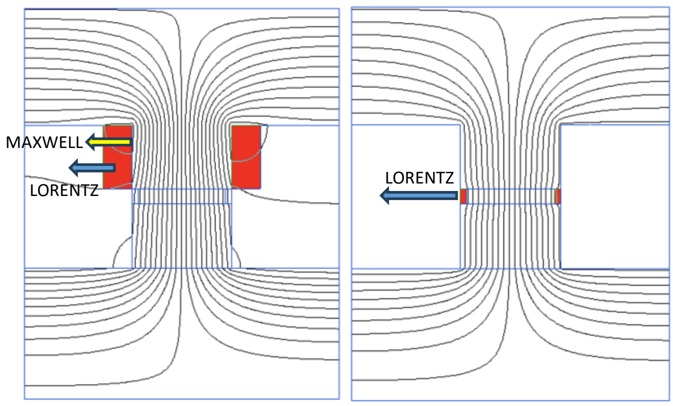


Figure 11a) Real machine field lines and force origin b) Simplified machine field lines and force origin (conductors shown in red)

In parallel, and from the initial dimensioning, an engineering conceptual design is also under development, based on the concepts shown in figure 7 (which is not to scale). The design is continuously evolving as more precise calculations and smarter ideas and solutions arise. The construction of the prototype will start in 2026, followed by partial and global testing of the prototype and its associated subsystems.

Additionally, to the development of the prototype, which includes the validation of the models and the projection of the results for real scale applications, there will be an additional WP for adapting the laboratory model to the two cases previously developed by the two technologists participating in the project. This stage will start defining the requested "External" parameters that the generator must fulfil for the specific application under exploration (i.e. force, velocity, stroke, size limits if applicable, etc.). With those inputs, the partners involved in STAGE 5 will pre-dimension the generator for each of the applications, allowing the developers of this Stage to know the approximate "internal" parameters of the generator (overall sizes, weight, etc.) to be integrated in the specific application once it has been fully defined also at this point. This exercise will be performed for two completely different WEC Systems (UNDIGEN & SYMPHONY). The analysis will also include a preliminary cost analysis and the impact of the solution in the LCOE of the full WEC.

VI. CONCLUSION

We have presented along this paper the fundamentals of a proposal for developing a superconducting reciprocating generator for wave energy conversion, but also for other applications where translation movements must be converted into electricity or vice versa. It leans on the concept of reciprocating generator based on a cylindrical switched reluctance machine and a flexible cryostat (with one moving and one stationary part) whose moving part is attached to the translator of the generator while the stationary one is fixed with the stator. Both parts of the machine are confined inside this flexible cryostat volume with no moving parts coming in or out from it. The selected machine is very simple, robust and cost effective and it includes MgB_2 based and ReBCO coils, refrigerated with a Cryogenic Supply System based on a closed-loop Gas Helium circuit in which heat losses are removed using a cryocooler.

There are ten partners involved in the project with clearly defined roles, spanning from fabrication and design of superconducting devices, development of superconducting wires or technologist in the field of wave energy conversion.

The project started in October 2024 and will last for four years from that date. At present, the partners are involved in the conceptual design of the generator whose fabrication should start early next year.

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