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Concept Design of a Novel Superconducting PTO Actuator for Wave Energy Extraction

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***Abstract*—The role of the Power Take-Off (PTO) as part of modern Wave Energy Converters is becoming more and more relevant and many efforts have been done or are ongoing to improve its performance especially in terms of force density and efficiency. Electric Linear PTOs are inherently the most efficient category, since they are really direct drives with no intermediate stages of energy conversion. Nevertheless, conventional electric machines are usually limited in force while their efficiency is better than other type of drives but still does not allow an intense energy capture in a broad band of wave periods. In this regard, superconductivity may become a very helpful alternative that allows improving both: efficiency and force density in spite of the technological difficulties that are introduced in the Wave Energy Converter.**

This paper, after justifying the need for better PTO performances, presents a new concept of superconducting PTO in which both, the stator and the translator work at cold temperature, performing a reciprocating displacement inside a flexible cryostat. The concept is later applied to a Cylindrical Switched Reluctance machine whose global design is also presented in the paper. This activity has been performed as one of the work packages of the EU H2020 Sea Titan Project in which also a resistive PTO with a novel configuration has been developed.

***Index Terms*— Linear generator, Power Take-Off, Superconducting device, switched reluctance machine, Wave Energy.**

I. INTRODUCTION

PTOs (Power Take-Off) have always been 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. For instance, the Joint Research Centre (JRC) has this priority since 2014 [1], [2] and the Strategic Research and Innovation Agenda for Ocean Energy still recognises in 2020 “improvement and demonstration of PTO and control systems” as a challenge topic and a priority for the design and validation of ocean energy devices [3]. As a result, the European Commission has funded several projects in recent years, addressing the development and optimisation of PTOs for wave energy conversion under the Horizon 2020 calls, such as OPERA, WaveBoost, WETFEET, IMAGINE and SEA-TITAN [4] in the frame of which the design presented here has been carried out.

In order to generate significant levels of power, PTOs for wave energy extraction must be able to produce big forces since the involved speeds are quite low. If, additionally, some extra force is required for tuning the device (reactive force), the needs can be even higher. Hydraulic and pneumatic PTOs have been considered since they are able to exert very high forces but they are not direct drive systems requiring further energy conversion stages which considerably reduce the overall efficiency. In this context, the development of direct drive electric PTOs, able to produce high forces with limited losses, has become very attractive. At this point, superconductivity appears as a conceptually perfect alternative: it allows increasing the force of the electrical machine (approximately proportional to the current), without increasing its losses (which, for a non-superconducting machine, depend on the square of the current).

All the above-mentioned considerations led the authors to participate in a H2020-Call named SEA TITAN, aimed at developing a new type of resistive electrical PTO based on a novel topology of switched reluctance machine (more compact and efficient) and also at performing a conceptual design of a superconducting PTO profiting from the advantages that superconductivity can bring to this application.

II. THE IMPORTANCE OF HIGH-FORCE/HIGH-EFFICIENCY PTOS

Previous arguments stressing the importance for a Wave Energy Converter of requiring a high force capability and a high efficiency can be illustrated in more detail by referring to the particular and extended case of Heaving Point Absorbers (HPA), which constitute one third of all types of WECs [5]. Figure 1.a presents an example of a two-body HPA. One is stationary or pseudo-stationary and is called ‘Spar’, while the other moves with respect to the former and is called ‘Float’. In

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between both of them there is a generic PTO in charge of transforming the linear movement into electrical power [6].

The HPA can be conceptually understood as a mechanical system onto which two external forces are acting: one is produced by the wave and the other by the PTO. The system is characterised by its mechanical impedance, which includes inertia, damping and buoyancy. A very convenient approach to analyse the behaviour of the PTO is to apply an electrical analogy in terms of an equivalent electrical circuit. Such circuit considers the two external forces as two generators coupled through an equivalent electrical impedance (inductance, capacitance and resistance) and allows answering the key question of what the value of the PTO generator voltage (force) should be in order to extract the maximum amount of energy from the waves.

Figure 1.b shows the aforementioned circuit with its corresponding elements: the two generators represented by the voltage sources, the impedance, the current flowing through it (which represents the moving speed) and, additionally, a resistor in parallel with the PTO force, associated to its losses.

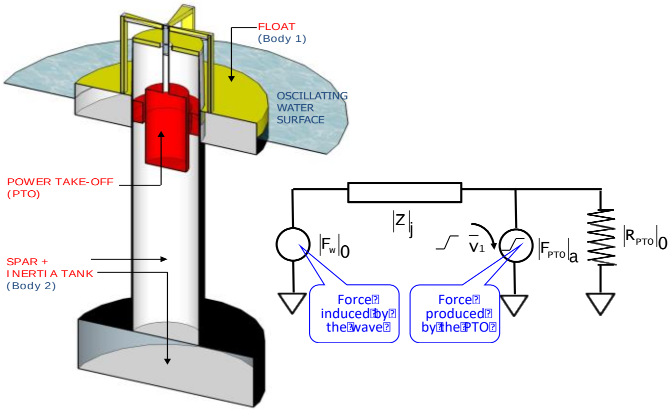

Fig. 1. a) Conceptual arrangement of a Heaving Point Absorber
b) Equivalent Circuit of a Heaving Point Absorber

Our objective is to calculate, using this equivalent circuit, which is the required force that must be exerted by the PTO of a given WEC (with its corresponding equivalent impedance) to harvest the maximum possible energy from waves of constant amplitude but different periods. The results of this analysis, are shown in Figure 2 for a real HPA developed and tested by some of the authors among others (under the UNDIGEN Project) some years ago [7]. The HPA included a resistive PTO based on a linear switched reluctance machine and a control strategy aimed at maximizing the generated electrical power [8]. The simulation is focussed on the calculation of the maximum power that can be extracted and the force that is required for that, in four different scenarios: 0) Ideal Case representing a theoretical limit: Placing in the referred HPA an ideal PTO with 100% efficiency and no force limit (curves (A) for the Force and (C) for the Power) 1) Placing in the HPA the original PTO with a force limit of 150 kN (curve (G) for the Power) 2) Changing the real HPA PTO with a hypothetical unit with a maximum efficiency of 85% and a force limit of 1MN (curves (E) for the Force and (F) for the Power) 3) Changing the real HPA PTO with a hypothetical unit with 100% efficiency and a force limit of 1MN (curves (B) for the Force and (D) for the Power).

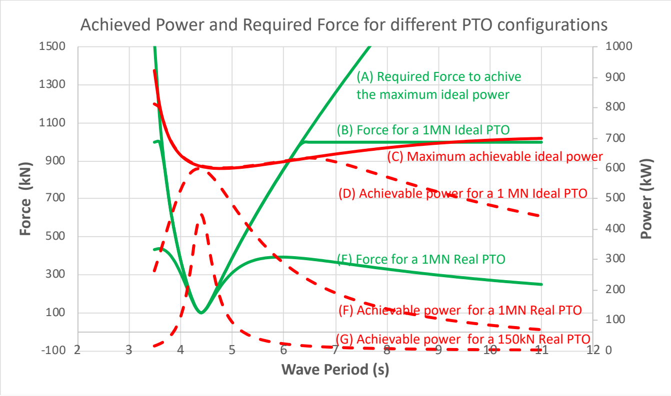

Fig. 2. Calculation the maximum extractable power and the required force for different PTOs placed in a same real HPA

Previous results lead to the conclusion that trying to harvest energy at wave periods far from the HPA's resonance by only increasing the PTO force is useless, although this force must be increased from the kN range up to the MN one, leading to much bigger PTOs. Even the relatively highly efficient machine considered in scenario 2) is limited by the Joule losses and it is not able to make use of its full force capability to extract the available power. In summary, superconductivity appears as a perfect ally of wave energy extraction for developing very efficient PTOs that can broaden the bandwidth of energy extraction.

III. A PROPOSAL FOR A NEW SUPERCONDUCTING PTO

Different types of conventional linear machines have been proposed as part of PTOs for wave energy conversion [9],[10],[11],[12],[13],[14],[15],[16], including those based on Switched Reluctance PTOs proposed by the authors [6],[7]. The restrictions imposed by the operation in the superconducting state limits the types of superconducting machines. More specifically, superconductivity has been limited to the DC side to avoid AC losses on the one hand, and it has also been mainly restricted to stationary windings to avoid the complexity of moving windings working at cryogenic temperatures. Alternatively, solutions for using bulk superconductors as high-field permanent magnets to create the excitation field have been proposed [17]. Most of this proposal or realisations are rotary machines, although there are also some linear superconducting actuators [18],[19],[20]. One interesting case for Wave Energy applications was the one proposed by Keysan and Mueller [21], based on a linear synchronous machine with superconducting DC excitation and normal conducting stator to avoid AC losses. The superconducting excitation may have homopolar or bipolar configurations and it is based on using a superconducting coil and an iron yoke to create a dipolar magnetic field which crosses the copper armature windings powered by electric current, creating a net thrust.

Generally speaking, and for the case of superconducting machines with only one superconducting side, there are three possible configurations depending on the working temperature of its elements, as depicted in figure 3.

Obviously, there is one main condition to fulfil: superconducting coils must be at cryogenic temperature; the rest can be either at cold or warm temperatures. Figure 3.a represents a configuration where only the SC coils are cold; figure 3.b another one with a fully cold stator (iron and coils) and a warm translator; and figure 3.c a fully cold machine. 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 [22]); and, finally, the third case needs an airgap of around 3 to 5 mm, big enough to allow the presence of a radiation screen but much smaller than in the second case. Apparently, the first case should be preferable to the other two since the airgap is the smallest one, 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 complicated.

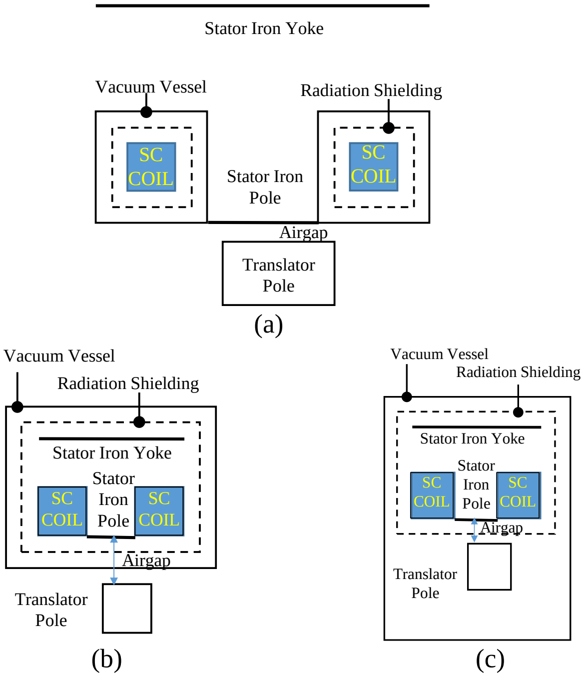

Fig. 3. (a) Only SC Coils working at cold. (b) Full Stator working at cold. (c) Full Stator & Translator working at cold

The solution presented in figure 3.b is extremely compact and coils are directly wound around the iron, simplifying their structural support. The problem now is the huge airgap which is needed and the corresponding associated stray field. Even if the ampere-turns are increased to compensate for the bigger gap, the machine becomes very inefficient from a magnetic point of view. Finally, the solution shown in figure 3.c, which is fully contained inside a cryostat, has the advantages of a relatively small airgap to guarantee an efficient electromagnetic design and an easy support of the coils, which can be directly wound around the iron to retain the electromagnetic forces.

Based on the third solution, we present a proposal for a superconducting linear-displacement PTO as shown in figure 4. The complete machine is allocated inside a flexible cryostat, formed by two upper and lower bellows attached to a central stationary body. The latter hosts the stator with the superconducting coils and the surrounding radiation screen. On its side, the translator is fixed to the moving parts of the cryostat, but it is thermally insulated from them. In reality, 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.

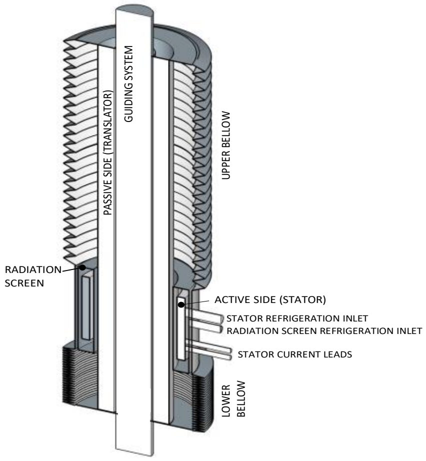

Fig. 4. Superconducting PTO concept based on a flexible cryostat.

IV. SUPERCONDUCTING SWITCHED-RELUCTANCE-MACHINE-BASED PTO

Following this configuration, different types of electrical machines could be implemented in a superconducting version (e.g. a permanent magnet tubular synchronous machines [23]). The authors have proposed and conceptually developed a solution based on a Superconducting Switched Reluctance Machine (SSRM) configuration in the framework of the H2020 EU SEA TITAN Project. It constitutes a completely novel approach and as far as the authors know, there are no previous related realizations. In fact, the idea has been recently granted with a national patent. Besides for the reason of exploring how a superconducting version of this type of machine could be, its inherent simplicity like the presence of coils in only the stationary side of the machine, the use of flat coils very easy to wind, or the extremely simple and robust configuration of the translator, make the Superconducting SRM a perfect candidate in spite the number of difficulties to be addressed like the AC losses or the cooling procedure. The approach that has been followed to perform this conceptual design is based on producing the same force as the conventional PTO that has been calculated, designed, fabricated and tested along the SEA TITAN project.

The first phase was the selection of the most convenient topology for the Superconducting SRM (SSRM). A similar configuration to what was done for the conventional version was soon discarded due to its complexity to be produced in a superconducting version.

Finally, the selected SSRM has a three-phase cylindrical topology [24] as depicted in figure 5. The superconducting coils are based on MgB_2 wires from the company ASG which also has been part of the SEA TITAN consortium. These coils are simply flat circular solenoids, very easy to wind as the required bending radius are bigger than those needed for the equivalent racetrack coils.

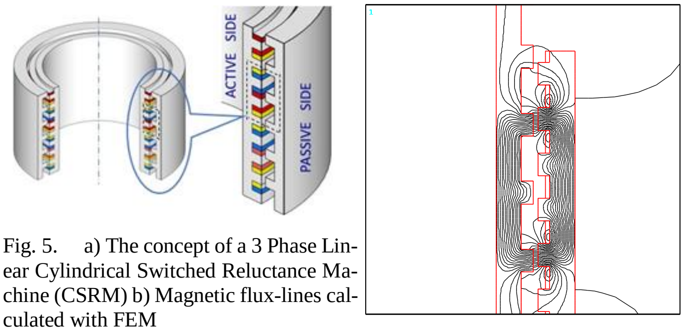

Fig. 5. a) The concept of a 3 Phase Linear Cylindrical Switched Reluctance Machine (CSRM) b) Magnetic flux-lines calculated with FEM

The electromagnetic design of the machine is based on an analytical model refined with FEM calculations to improve the accuracy in the estimation of the electromagnetic force, essentially. Table I shows a comparison between the Cylindrical SRM in the superconducting version (SSRM) and a Cylindrical SRM in the resistive one (RSRM), both designed to provide the same force as the SEA TITAN machine.

As it can be noticed from table I, the reductions in the dimensions and particularly in the weight are enormous with the subsequent impact in the overall sizes of the Wave Energy Converter. Both machines have been designed to work at the same (and lowest possible) commutation frequency to reduce to a minimum a.c. losses, although the resistive one doubles the stroke of the superconducting version since it is not constrained by the flexible cryostat size limitations.

TABLE I
COMPARISON BETWEEN THE SUPERCONDUCTING AND THE RESISTIVE SWITCHED RELUCTANCE MACHINES

PARAMETER	SSRM	RSRM
Nominal Force	35.0 kN	35.0 kN
Force calculated with FEM	36.2 kN	--
Conductor	MgB_2 @ 10k	Copper
B_{max} in the magnetic circuit	2.7T	2.1T
B_{max} in the superconductor	1.9 T	--
Required Ampere-Turns	17824 A	8361 A
Operational Current	208 A	625A
Stator height	244 mm	733 mm
Diameter at the airgap	344 mm	944 mm
Conductor weight	5.3 kg	3296 kg
Stator Iron weight	63.5 kg	1568 kg
Overall Stator weight	68.9 kg	4864 kg
Stroke	± 1.5m	± 3.0m
Commutation frequency	15 Hz	15 Hz

Concerning the conceptual implementation, figure 6 shows the general arrangement of the proposal and includes the current leads (1), the radiation screen (2), the active superconducting side (stator) (3), the passive iron side (4) and the bellows of the flexible cryostat (5).

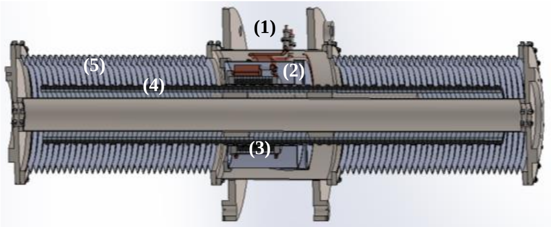

Fig. 6. Global design of the Superconducting Switched Reluctance Machine with flexible cryostat.

The main identified issues and the corresponding proposals to overcome them, are presented in table II and they will constitute some of the challenges for future works on the project.

TABLE II
ISSUES AND SOLUTIONS FOR THE SUPERCONDUCTING SWITCHED RELUCTANCE MACHINE

MAIN ISSUES	APPROACH/SOLUTION
AC losses in the Stator	Reducing the wire filament, increasing the matrix resistivity and reducing the twist pitch
Losses in the Radiation Screen	Non-metallic radiation screen refrigerated with LN2
Limited Cryostat elastic spring constant	Limited wall thickness and fabrication process
Cryostat max. number of cycles	In the range of 10,000,000 for a duration of 6 years
Cryostat Extended/Compressed ratio	Also depending on the bellow fabrication process. In the range of 3.5

This paper has only tackled the conceptual design of the machine but additional work is also going on in the power converter (based on well-known topologies for grid-connected SRMs in single pulse operation to avoid high order harmonics and consequently a.c. losses) and the use of a novel refrigeration system developed by the authors for other applications.

V. CONCLUSIONS

High force direct-drive PTOs constitute an interesting option to increase the energy that can be harvested from ocean waves as it can be concluded from the results presented section II, based on the use of an equivalent electrical analogy. At the same time, these results also conclude that a high force PTO is useless if its efficiency is not high enough, and here is where a linear superconducting machine, can be very convenient.

The analysis of linear machines with superconducting stators presented in section III concludes that two options are possible: a) only cold coils b) cold coils and cold stator iron. The first leads to coils with poor overall current densities while option b) leads to machines with enormous airgaps. The authors have proposed in this paper a topology in which stator coils and iron and also the translator, are inside a flexible cryostat performing a reciprocating movement with a limited stroke, confirming its fully applicability to PTOs for wave energy extraction.

The last section of the paper develops a specific solution based on a Cylindrical Switched Reluctance Machine concluding its suitability for this application. The main concern are the ac loses and its analysis will be part of future developments as the well as the cryosystem and the power converter.

REFERENCES

[1] D. Magagna, R. Monfardini, and A. Uihlein, “JRC Ocean Energy Status Report 2016 Edition,” 2016.

[2] D. Magagna and A. Uihlein, “2014 JRC Ocean Energy Status Report,” Publications Office of the European Union, Luxembourg, EUR 26983 EN (JRC 93521), 2015.

[3] J. L. Villate et al., “Strategic Research and Innovation Agenda for Ocean Energy,” Etipocean, no. 826033, p. 64, 2020.

[4] WEDGE GLOBAL, “SeaTitan,” 2018. [Online]. Available: https://seatitan.eu/. [Accessed: 29-Nov-2021].

[5] E. Commission, “SEA-TITAN: Surging Energy Absorption Through Increasing Thrust And efficieNcy | SEA-TITAN Project | H2020 | CORDIS | European Commission,” 2018. [Online]. Available: https://cordis.europa.eu/project/rcn/214624/factsheet/es. [Accessed: 19-Aug-2021].

[6] L. Garcia-Tabares et al., “New Type of Linear Switched Reluctance Generator for Wave Energy Applications,” IEEE Trans. Appl. Supercond., vol. 30, no. 4, Jun. 2020.

[7] PLOCAN, “Plataforma Oceánica de Canarias | PLOCAN - Projects.” [Online]. Available: https://www.plocan.net/index.php/en/projects. [Accessed: 27-Nov-2021].

[8] M. Blanco, M. Lafoz, G. Pinilla, L. Gavela, and A. Echeandia, “Electric Linear Generator to Optimize a Point Absorber Wave Energy Converter,” Proc. 3rd Int. Conf. Ocean Energy (ICOE 2010), pp. 1–5, 2010.

[9] A.A. Faiad, I.A. Gowaid “Linear Generator Technologies for Wave Energy Conversion Applications: A Review”.
DOI 10.1109/UPEC.2018.8542007. Sep 2018

[10] A. Kladas et al. “Overview of Alternative Topologies of Linear Generators in Wave Energy Conversion Systems” Material Science Forum. June 2012.

[11] L. Huang, M. Chen, L. Wang, F. Yue, R. Guo, and X. Fu, “Analysis of a Hybrid Field-Modulated Linear Generator for Wave Energy Conversion,” IEEE Trans. Appl. Supercond., vol. 28, no. 3, Apr. 2018.

[12] J. Zhang, H. Yu, Q. Chen, M. Hu, L. Huang, and Q. Liu, “Design and Experimental Analysis of AC Linear Generator with Halbach PM Arrays for Direct-Drive Wave Energy Conversion,” IEEE Trans. Appl. Supercond., vol. 24, no. 3, Jun. 2014.

[13] J. Prudell, M. Stoddard, E. Amon, T. K. A. Brekken, and A. Von Jouanne, “A permanent-magnet tubular linear generator for ocean wave energy conversion,” IEEE Trans. Ind. Appl., vol. 46, no. 6, pp. 2392–2400, Nov. 2010.

[14] T. Xia, H. Yu, R. Guo, and X. Liu, “Research on the Field-Modulated Tubular Linear Generator with Quasi-Halbach Magnetization for Ocean Wave Energy Conversion,” IEEE Trans. Appl. Supercond., vol. 28, no. 3, Apr. 2018.

[15] H. Polinder, M. E. C. Damen, and F. Gardner, “Linear PM generator system for wave energy conversion in the AWS,” IEEE Trans. Energy Convers., vol. 19, no. 3, pp. 583–589, Sep. 2004.

[16] M. A. Mueller, “Electrical generators for direct drive wave energy converters,” in Proceedings of the Generation, Transmission and Distribution, IEE, 2002, vol. 149, pp. 446–456.

[17] O. Farrok, M. Islam, M. Sheikh, Y. Guo, J. Zhu & W. Xu, "A Novel Superconducting Magnet Excited Linear Generator for Wave Energy Conversion System," IEEE Transactions on Applied Superconductivity, vol. 26, (7) pp. 5207105-1-5207105-5, 2016.

[18] L. Huang, B. Hu, M. Hu, C. Liu, and H. Zhu, “Research on Primary Excitation Fully Superconducting Linear Generators for Wave Energy Conversion,” IEEE Trans. Appl. Supercond., vol. 29, no. 5, Aug. 2019.

[19] Y. Terao, M. Sekino, and H. Ohsaki, “Design study of linear synchronous motors using superconducting coils and bulks,” 2010 Int. Power Electron. Conf. - ECCE Asia -, IPEC 2010, pp. 1760–1765, 2010.

[20] J. X. Jin, L. H. Zheng, Y. G. Guo, and J. G. Zhu, “Performance characteristics of an HTS linear synchronous motor with HTS bulk magnet secondary,” IEEE Trans. Ind. Appl., vol. 47, no. 6, pp. 2469–2477, Nov. 2011.

[21] O. Keysan and M. A. Mueller, “A linear superconducting generator for wave energy converters,” IET Conf. Publ., vol. 2012, no. 592 CP, 2012.

[22] J. Munilla et al., "Cold Tests and Magnetic Characterization of a Superconducting Magnet for a Compact Cyclotron for Radioisotope Production," in IEEE Transactions on Applied Superconductivity, vol. 28, no. 3, pp. 1-5, April 2018, Art no. 4400505, doi: 10.1109/TASC.2017.2775582.

[23] A. Souissi, I. Abdennadher, and A. Masmoudi, Tubular-Linear Synchronous Machines: Application to Wave Energy Harvesting. Singapore: Springer, 2019.

[24] R. P. G. Mendes, M. R. A. Calado, and S. J. P. S. Mariano, “Identification of some tubular topologies of linear switched reluctance generator for direct drive applications in ocean wave energy conversion,” Lect. Notes Eng. Comput. Sci., vol. 1, pp. 396–400, 2014.