CEN WORKSHOP AGREEMENT

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Recommendations for a modular and cross-cutting Power Take-Off for wave energy direct drive linear solutions

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CEN-CENELEC Management Centre: Rue de la Science 23, B-1040 Brussels

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Foreword

CWA 50271:2021 has been developed in accordance with the CEN-CENELEC Guide 29 "CEN/CENELEC Workshop Agreements – A rapid prototyping to standardization" and with the relevant provisions of CEN/CENELEC Internal Regulations – Part 2. It was approved by a Workshop of representatives of interested parties on 2021-02-10, the constitution of which was supported by CEN-CENELEC following the public call for participation made on 2020-06-10. However, this CEN-CENELEC Workshop Agreement does not necessarily include all relevant stakeholders.

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The following organizations and individuals developed and approved this CEN-CENELEC Workshop Agreement:

- CENTIPOD LTD., Mr. Alan McCall
- CIEMAT, Mr. Marcos Lafoz
- CIEMAT, Mr. Marcos Blanco
- CIMEAT, Mr. Miguel Santos
- CIEMAT, Mr. Luis García-Tabarés
- CORPOWER OCEAN, Mr. Matt Dickson
- Fabricom NV (ENGIE), Mr. Luka Vanderplancke
- HYDROCAP ENERGY SAS, Mr. Alain LARIVAIN
- NEW R&D – CNET (EDP), Mr. Christian Verrecchia
- NEW R&D – CNET (EDP), Mr. Tiago Lourenco
- OCEM Energy Technology, Mr. Mattia Mantellini
- OCEM Energy Technology, Mr. Miguel Pretelli
- WEDGE GLOBAL S.L., Mr. Aleix Arenas

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Introduction

The EU's Energy Roadmap states that renewable energy should make up at least 64 % - and up to 97 % - of electricity consumed by 2050. Wave and tidal energy remain an untapped source of power, which could prove critical to enabling Europe to meet this commitment. Furthermore, according to the "Strategic Research and Innovation Agenda for Ocean Energy" published in May 2020 by the European Technology & Innovation Platform for Ocean Energy (H2020 grant agreement 826033) one of the challenge areas identified for Wave Energy Technology is the design and validation of ocean energy devices, in particular, the improvement and demonstration of PTO and control systems where one of the expected impacts is aligned with the purpose of this document: *"Convergence (standardization) and simplification of designs to allow a reduction in maintenance costs".*

Currently each original WEC equipment manufacturer offers its own solution for the wave energy conversion technology, pursuing the development of bespoke technology without a common approach or objective not only limits the utility of the end product but also multiplies the development time and costs. Wave energy convergence represent an approach to a more sustainable and integrated industrial economy which identifies business opportunities to enable industrial processes and mass scale production.

Enabling this convergence requires the identification of the core elements shared in common between most of the WEC technologies being developed in the recent years, so synergies can be found between them and common industrial solutions can be proposed, focusing the R&D efforts where relevant for each developer, channeling the innovation present within any and all of the different WEC projects or developments (best value for money) while also reducing risk associated with the innovation process. For this to happen however, the wave energy sector needs to achieve economies of scale and have access to reliable technology and a dedicated supply chain.

This document has been developed in the frame of the project H2020 SEA TITAN (Grant Agreement No. 764014).

1 Scope

This CEN Workshop Agreement (CWA) document provides recommendations for good practice implementation of Modular and Crosscutting Power Take Offs (PTO) for wave energy linear direct drive technologies, in addition, a switched reluctance case study will be presented. Any wave energy technology developer or associated stakeholders should find here guidance and recommendations to consider and adopt a Modular and Cross-cutting linear direct drive PTO technology.

Consensus on the core elements for Modular and Cross-cutting PTO technology is provided to enable its identification, definition and design recommendations or guidelines, including mechanical, electric, power electronics and control elements. Specifically, this CWA sets out the following:

1) Core elements for a cross-cutting and modular PTO.

2) Relevant interfaces for modular and cross-cutting PTO implementation.

3) Annex: SEA TITAN linear switched reluctance PTO.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC/TS 62600-1, *Marine energy — Wave, tidal and other water current converters — Part 1: Vocabulary*

IEC/TS 62600-2, *Marine energy — Wave, tidal and other water current converters — Part 2: Marine energy systems — Design requirements*

IEC/TS 62600-100:2012, *Marine energy — Wave, tidal and other water current converters — Part 100: Electricity producing wave energy converters — Power performance assessment*

3 Terms, definitions and abbreviation

3.1 Terms and definitions

For the purpose of this document, the following terms, definitions and abbreviations apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

— IEC Electropedia: available at https://www.electropedia.org/

— ISO Online browsing platform: available at https://www.iso.org/obp

3.1.1
prime mover
physical component that acts as the interface between the marine resource and the energy converter from which energy is capture

Note 1 to entry: For wave energy converters the prime mover may be a heaving buoy, hinged flap, an OWC runner, etc.

[SOURCE: IEC TS 62600-1:2012]

3.1.2
Power Take Off
mechanism that converts the motion of the prime mover into a useful form of energy such as electricity

[SOURCE: IEC TS 62600-1:2012]

3.1.3
modular design
design that clearly present single units of standardized size, design or construction, acting as the minimum, indivisible and stackable element for the normal operation of the complete machine that can be arranged or fitted together in a variety of ways depending on the overall design

3.1.4
cross-cutting design
design that may be easily adopted by most of the existing wave energy converter solutions, with none to minimal modifications required

3.1.5
primary structure, marine energy converter
collective system comprising the structural elements, foundation, mooring and anchor, piles, and device buoyancy designed to resist global loads

[SOURCE: IEC TS 62600-2:2016]

3.1.6
point absorber device
WEC that is small relative to the wave length and typically absorbs wave energy independent of the direction of wave incidence

[SOURCE: IEC TS 62600-1:2012]

3.1.7
conversion efficiency (wave-to-wire efficiency)
measure the overall effectiveness of a marine energy converter calculated as the ratio of electrical power output in relation to the incident power in the water resource

[SOURCE: IEC TS 62600-1:2012]

3.2 Abbreviations

WEC	Wave Energy Converter
CWA	CEN Workshop Agreement
PTO	Power Take Off
R&D	Research and development
HLC	High Level Control
LLC	Low Level Control
IGBT	Insulated Gate Bipolar Transistor
MC	Modular and Crosscutting

4 Modular and Cross-cutting PTO core units

4.1 Mechanical modular unit

4.1.1 General

Any linear direct drive MC PTO is composed by two clearly identifiable elemental units easily configurable and stackable for different WEC setups according to the overall design in hands or needs of any particular existing equipment (housing, forces, velocities). This section presents the core units for a MC PTO and some recommendations to consider for technology implementation.

4.1.2 Translator

The translator is the moving component of the generator. It is driven into motion by the prime mover. Depending on the system's overall design, multiple translator characteristics should be considered:

- Role: Translator as the active element (coils or windings) or the passive element (magnetic cores).
- Position: Installed either inside or outside of the stator unit. Affects the interface requirements.
- Length in relation with the stator unit: Affects the required space and costs.

4.1.3 Stator

The stator is the stationary design component of the system. It works with the translator and, like the translator itself, it can be either the active or the passive part to be installed inside or outside of the translator unit.

4.1.4 Configuration recommendations

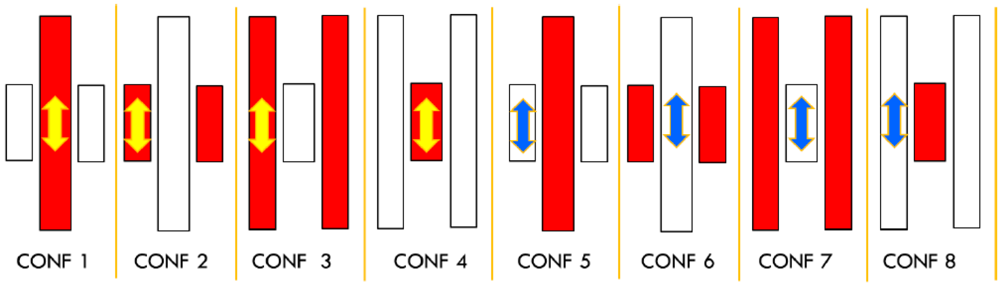

Figure 1 — Translator and stator possible configurations – Arrows (blue or yellow) for translator unit, Red for active unit

Ideally, eight configurations may be found, it is recommended to consider the following notes for the translator unit, stator unit will be configured to complement the decisions made on the translator:

- Translator longer than stator: The required housing for the PTO is doubled.
- Translator as the active element: Requires flexible cabling and energy chain.
- External translator: May require additional prime mover to translator interfaces.

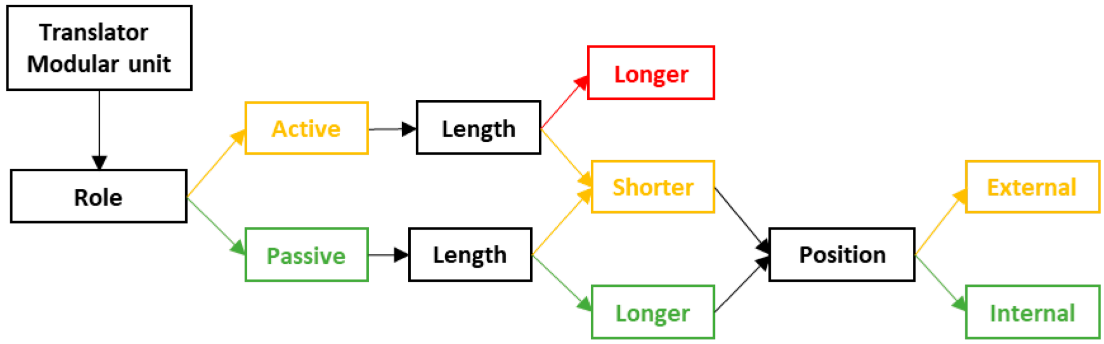

Figure 2 — MC PTO configuration recommendations from translator perspective

Some particular combinations are highly not recommended and should be avoided if possible unless specific requirements take place (laboratory testing or similar). Technology specifications and cost shall be considered when deciding the PTO configuration, looking to achieve an economic optimum.

Recommended combinations are:

- Configuration 4: Active shorter internal translator. Passive longer external stator.
- Configuration 6: Passive longer internal translator. Shorter active external stator.

Some benefits and drawbacks are present for the recommended combinations and shall be analyzed depending on the final application of the MC PTO between laboratory or real sea.

	Configuration 6	Configuration 4
Benefits	• Lighter Passive Side. • No need for energy chain or flexible cabling.	• Stator may be integrated within primary structure, no main frame > lower cost. • Easier to achieve stiffness. • Shorter primary structure.
Drawbacks	• More housing required > longer primary structure. • Higher moving weight > Higher loads on the guiding system. • More difficulty to achieve Passive Side Stiffness.	• Need for an Energy Chain and flexible cabling. • Heavier Passive Side. • More difficult access to the Active Side.

Figure 3 — Benefits and drawbacks to consider for a real sea MC PTO application

	Configuration 6	Configuration 4
Benefits	• Smaller Passive Side weight. • Better accessibility to coils or windings and the guiding system. • Possibility to additionally guide the Active side on a moving chariot acting as a motor	• The possibility of reproducing the Passive Side as part of the primary structure. • Introduction of as many supports and fixations to the ground as desired.
Drawbacks	• Achievement of the required stiffness in the Passive Side. • Intermediate supports of the Passive Side	• Less space for supporting the coils or windings from the inner side • Restricted access to the Active Side. • No space for a moving Power Converter

Figure 4 — Benefits and drawbacks to consider for laboratory MC PTO application

4.1.5 Modular unit selection criteria

Some of the recommendations present in this section can be generally applied to any kind of electrical machines, but it is of particular interest when defining the modular unit for any MC PTO.

<u>Force and stroke</u>

The first step to define any modular unit is to get the optimal force to be achieved by the PTO. The force and stroke specifications can be defined by analyzing the WEC geometry and the deployment location, choosing the right number of modules whose stacking meets the specifications. It shall be analyzed under different considerations for both, WEC geometry and locations so that the modular unit can meet the requirements of the greatest number of situations with the least overall deviation of requirements. That is, for each situation a different number of modules will be needed, and since the number of modules is an integer, the characteristics of the complete PTO will be higher or lower than those required, producing a deviation. Thus, a force will be defined for the modular unit that minimizes the force deviation for the largest number of cases. An excess in the force deviation means a higher power extraction but it would not be proportional to the increment of PTO CAPEX.

<u>Winding configuration, phases and poles</u>

The winding design shall fulfill the force requirements previously calculated; this is the main definition criteria and shall be strictly analyzed, afterwards, other parameters may be considered such as voltage limitations, materials, magnetic fields, geometry constrains, etc. On the other hand, the winding should also admit the stray fields and Lorentz forces generated during the system operation.

Each winding design for the active side shall consider the following set of initial parameters:

- Working Flux Density (Bo)
- Inner Radius (R)
- Airgap (g)
- Passive Pole Width @R (p)
- Winding Current Density (J)
- Iron B-H Curve (Flux density – Magnetic field strength)

- Number of Unit Cells (M)
- Overall Winding Radial Length (L)

and the following calculation procedure:

1) From the B-H curve interpolating the H value corresponding to B_0.
2) From the B-H curve calculation of the co-energy density curve and interpolation of the co-energy for the B_0 value.
3) Calculation of the UNIT CELL width@ R; A1 = 2·π·R/M and @ R+L/2 A2 = 2·π·(R+L/2)/M.
4) From the B-H curve calculation of the required NI (ampere-turns) for the specific geometry

   $NI(B) = (2 \cdot g \cdot B / \mu_0) + H(B) \cdot (A2 - 2 \cdot g)$

   where

   N number of turns in the winding;

   I electric current through the circuit [A].
5) From the calculated NI-B curve. Calculation of its area as a function of NI and calculation of NI value corresponding to B_0.
6) Calculation of the pole height = 2·h and the UNIT CELL height = 4·h.
7) Calculation of the co-energy corresponding to VI for B0 and the co-energy corresponding to VF for $B = \mu_0 \cdot NI/(2 \cdot g+p)$. Calculation of the force from the co-energy variation and extension to M windings. (VI & VF are defined in previous slide).
8) Calculation of the Lorentz Force per winding = Area [NI-B] B_0 and extension to M windings. Analyzing the force of the complete modular unit, validating with the initial force parameter from previous steps. If modular unit force is not achieved the calculation procedure shall be resumed starting from step 1.
9) Calculation of the active side weight from dimensions.

4.2 Electric requirements for modular units

Based on the power, maximum current, maximum voltage, stroke, velocity and winding design, the distribution of modular units will be obtained, considering the number of modules connected in series and/or parallel. Based on the number of modular units to be fed by each power electronics module, the number of stacked modular units (stacks) and type of connection (serial or parallel) will be defined. This definition will depend on the currents and voltages to be handled:

Serial connection, the current of the stack is equal to that of a modular unit while the voltage is equal to that of a modular unit multiplied by the number of units.

Parallel connection, the voltage of the stack is equal to that of one modular unit while the current is equal to that of one modular unit multiplied by the number of units.

The decision shall find a compromise solution between high voltages implying multilevel converters or high currents increasing losses in power electronics. This decision is related to the design of power electronics systems, defining the modular unit of power electronics.

4.3 Power electronics requirements for modular units

Starting from the current, the DC voltage and the maximum switching frequency values defined for the modular units, the design of power electronics conversion stage will be obtained.

Power electronics is divided into two parts: the GSC (Generator Side Converter) and the GTC (Grid Tied Converter), coupled through a common DC bus. The whole system realizes a back to back connection, where the GSC is connected to the generator and shares a common DC bus with the GTC which is connected to the grid.

The GSC shall be made up of three H bridge converters (half bridge configuration is enough for SEA TITAN application) since phases of the machine must be energized independently one from another (in order to improve controllability). Thanks to this, the GSC is easy shapeable to suit a circular section room, particularly by splitting the common DC bus into three equal parts and distribute them among each H bridge. This point is very important since the final application will host the converter in a circular room with many space issues and it becomes fundamental to save as much space as possible.

The dimensioning of the DC bus must be done to limit the DC voltage oscillation and to withstand the ripple current derived from the IGBT switching. Maximum reached temperature of the capacitors must be also verified by means of proper simulations.

The cooling system is very important too because it must be able to work with liquid cooling, exploiting sea water to subtract heat from the working power electronics in the final application. Thus, the cooling system design must be properly carried out via calculations and evaluations.

Due to maintenance reasons, the power electronics apparatus should be as compact as possible, in order to facilitate any type of intervention in accordance with the overall design of the PTO. Maintenance in a dimensionally strict environment must be as simplified as possible, so each part must be easy to be moved and replaced and components spare parts must be easy to purchase, since any repair time means energy production loss.

Temperature monitoring becomes fundamental both on switching transistors (the most failure-prone parts) and on heatsinks (to ensure they are well working). Proper systems to detect any failure of the heat extraction apparatus must be designed.

The electrical protection can be performed via fuses on the three phases and on the DC bus.

Fundamental variables which must be acquired by the measurement system are phase currents and phase voltages. Other signals must be managed by the control system and must be acquired through the power electronics apparatus, such as any fault protection device intervention and the status of any relevant subsystem.

In order to interface the power electronics with the control system, an adaptation interface for sensors and actuators including acquisition and conditioning circuits must be designed. Hardware safety intervention must be foreseen too, to act in redundancy with software safety systems.

Regarding the GTC, it can be a normal three phase converter with a proper control system to interface with the grid. An appropriate communication interface between the GSC and the GTC must be set up in order to exchange important information such as state of the GTC/GSC and permission to turn the GSC ON.

4.4 Control requirements for modular units

The control units will be considered according to the number or power electronic converters (section 4.3). It should be recommended a certain number of low-level control units associated to each power electronic converter unit and an additional global high-level control unit to govern the whole system.

<u>Low level control (LLC)</u>

Each one of the power electronic units feeding a group of PTO modular units shall have a LLC module. This module will receive current/force as a setpoint from the high-level control (HLC) and impose the switching states on the power electronics semiconductors to follow that setpoint. In this way, each LLC module will control the electrical variables in the governed PTO stacks.

All control modules will be connected to a HLC system (not modular) that will define the force or current setpoint at each instant and transmit it to the low-level control modules. In turn, the LLC modules will send information to the HLC module:

— Required: Stack status (operation, forced stop, position, communications, etc.).

— Optimal: information on the performance of the cluster (power generated by all of the stacks).

— Optional: information for monitoring the cluster (currents, voltages, force, speed, etc.).

The communication line between the LLC modules and the HLC should be unique (multipoint communication) and CAN type, although other options such as RS485 with own protocol, CANOPEN, or MODBUS RTP would be admissible. Additionally, it is recommended for each LLC module to have a point-to-point communication for monitoring during commissioning and debugging, not connected to the HLC and ready to connect directly to a PC type host.

High Level Control (HLC)

The HLC unit shall be configured according to the requirements and expected operation for each particular WEC technology. It is recommended to model the control system to obtain maximum electrical power output for the most relevant wave scenarios where it will be operating.

1) Representation of the wave climate – It is recommended to use the traditional scatter diagram representation making it easy to identify wave heights and periods for the location of interest. This table shall be fed with 10 years of information according to IEC TS 62600-100:2012. Other representations such as extensive or abridged may be valid.

2) HLC key parameters optimization. Any HLC involves a number of pre-generated and real-time inputs to be operated in some specific way depending on the technology or development in order to obtain a certain force or voltage command for the LLC. Real time inputs may involve wave prediction, position or velocity of the PTO among others. Pre-generated inputs involve a set of numbers to be used according to the wave scenario present at any given time and must be optimized beforehand in a numerical model such as WEC-SIM or similar. It is recommended to optimize these pre-generated coefficients looking to maximize the electrical output, so It can be used to properly select the modular unit and optimize cost. Force or Mechanical power optimization shall be avoided.

5 Relevant interfaces for MC PTO implementation

5.1 General

The following interfaces features modularity and cross-cutting capacity:

5.2 Main frame

The main frame is the housing of the PTO, a structural interface holding or supporting all the necessary parts and components, acting as interface between the PTO and the holding structure or platform. We can differentiate between testing and production main frames.

Testing Main Frame

Intended for laboratory purposes testing main frame should be designed to allow the generator to sit on the ground, a concrete pad, primary structure PTO frame or be mounted to a trailer for easy transportation of the system. It also helps ensure that the generator is properly grounded or earthed, which is essential for property operation and the safety of the system.

All of the mechanical loads are transferred to the main frame before dissipating in the holding structure or platform, but heat dissipations, and it should be designed accordingly to the expected loads to hold the integrity and security of the PTO. Loads to consider are weights (directly related to modular units), bending moments and shearing forces (when PTO is operating). Additionally, if the PTO is meant to sit on the ground (e.g.: laboratory purposes) it is recommended to include damping materials for vibrations (and noise replication) as an interface between the floor and the PTO, directly mounted on the main frame or alternative commercial solutions (e.g.: damping pad mats).

Production Main Frame

The Production Main Frame should be designed to meet two basic objectives:

1) Support and contain all PTO components, maintaining desired spatial arrangement of the PTO subsystems.

2) Enable repeatable interfacing of the PTO mechanical system as an independent unit with the larger WEC mechanical system.

With respect to objective 1, the challenge is similar to that of the testing main frame. It is expected that prior to the design of a production PTO system, the engineering team will have achieved objective 1. Therefore, the difficulty is expected to lay within achieving objective 2. Moreover, this challenge extends beyond the sole influence of the PTO technology developer, as the Production Main Frame must interface with a WEC system that may be of the same engineering team's design, but frequently may not. This section aims to lay a framework for an agreeable approach to the Production Main Frame interfaces with collaboration of WEC and PTO developer perspectives.

In the most basic sense, the job of a mechanical interface is to transmit loads between one mechanical structure (the WEC structure) and another (the PTO Production Main Frame). Since these systems are likely to be independently fabricated and joined in the final assembly stage, a general consideration will be given towards bolted connections rather than more permanent connections such as welds. The fundamental task is therefore to define the bounding box of the PTO system, so it can fit within the WEC without mechanical interference during and after assembly, and the bolt pattern, ensuring alignment between the prebuilt structures in assembly.

The first task in approaching this challenge is laying out a set of nomenclature for commonality in discussing interface design schema.

WECs currently in the sector typically have tubular structural components, and as a result the template will be made intuitive for this type of design by defining circular arrays with radii and angles rather than in cartesian coordinates. However, it should be noted that this template can be adapted to other cross sections.

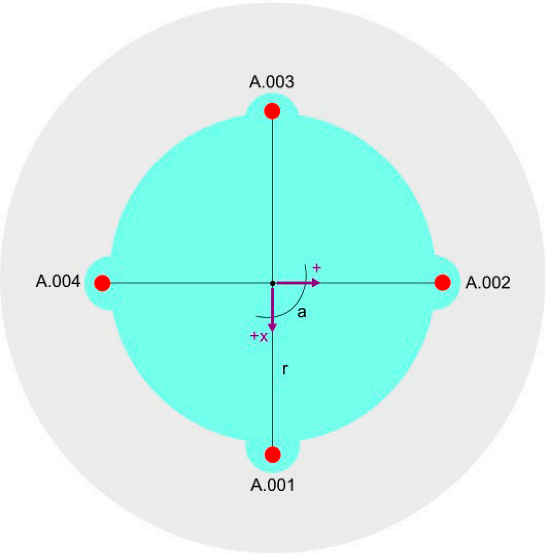

Figure 5 — Example planar connection point array

The entire system uses the center of the PTO at the highest vertical position as the origin and datum. Using the first connection point (pt001) as the beginning of the naming scheme, the numbering increments each connection point counterclockwise around the circular array drawn on the x-y plane in the tubular structure cross section. Once defined, this array is an instance of the plane class. A plane instance is then assigned to each plane in which connection points are present in the lengthwise, z direction and lettered starting from 'A'. In this manner the first connection point is A.001.

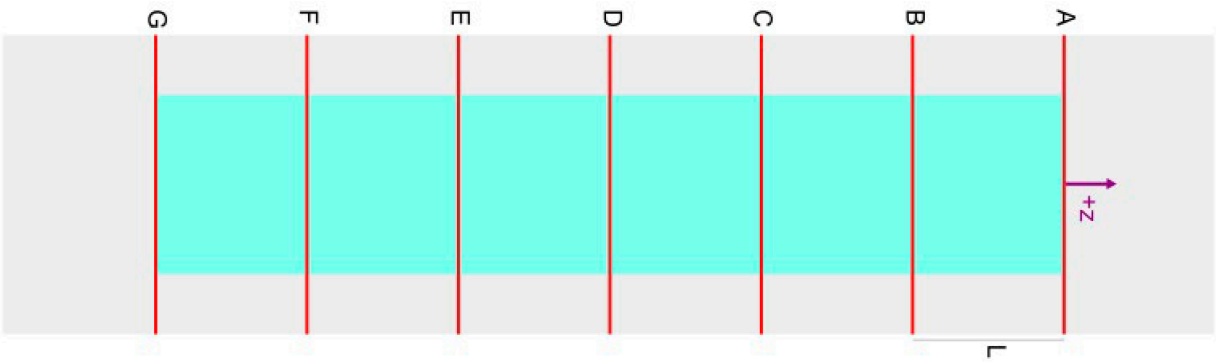

Figure 6 — Example array of planes in z direction

Plane Class		
property	value	unit
name	'typeA'	
alpha	90	deg
number	4	points
radius	1100	mm
Connection Point Definitions		
X.001	'type01'	
X.002	'type01'	
X.003	'type01'	
X.004	'type01'	

Plane Array		
name	z pos (mm)	instance
A	0	'typeA'
B	-1000	'typeA'
C	-2000	'typeA'
D	-3000	'typeA'
E	-4000	'typeA'
F	-5000	'typeA'
G	-6000	'typeA'

Figure 7 — Example table representing mechanical interface

Key design points to consider

Testing main fame considerations about mechanical loads previously presented remains valid.

The heat generated by a functioning PTO should be calculated and compensated by the installation of properly dimensioned heat sinks or cooling devices. For a fully functioning PTO, cooling by seawater seems the most obvious choice. In laboratory environments, other methods of cooling should be studied.

The main frame of a PTO designed for operation in the sea should be designed with regard to the harsh environmental conditions it will be put in. Therefore, the following issues need to be studied during design of the PTO:

— Coatings on materials;

— Use of stainless steel;

— UV proof materials;

— Shock & vibration resistance;

— Salt water resistance;

— Ingress Protection (IP) grade;

— Sealing between ‘wet’ and ‘dry’ parts of the PTO.

Due to the difficulties of maintenance on the main frame – and especially on the bigger components, all components of the main frame should be designed for long lasting life and operation. Smaller components (bolts, nuts, etc.) should be subjected to the same points of attention as mentioned earlier (coatings, UV proof, etc.) with special attention to the shock and vibration resistance.

Bounding box

The bounding box for the PTO frame is defined on the array instance level, with two basic options, a) the space contained within the connection points by straight lines, or b) arcs between connection points of a defined radius, the simplest case being that which is shown in Figure 05 creating a circular cross section.

By combining different instances of connection points and planes, this methodology can be used to define more complex mechanical interfaces with multiple fastener types, irregular spacings and bounding boxes varying along the length of the PTO system. Moreover, it gives a common method of defining the interface across multiple PTO and WEC devices designed by various teams.

Connection points

Each connection point must be defined with certain parameters such as maximum load, bolt orientation, nominal bolt size, bolt material etc. To save time, a connection point class is constructed and instances can be defined and assigned to multiple or all fasteners. Bolt or pin orientation can be defined using the Main Frame coordinate system by defining the angle with respect to the x-y, x-z, or y-z planes.

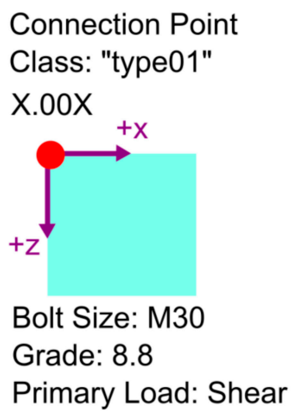

Figure 8 — Example definition of a Connection Point class instance "type01" with a through hole on the x-z plane

5.3 Electrical connectors

Modular design configuration may result for incompatible connector configuration. The electrical connections configuration shall be designed to guarantee the correct and safe connectivity between adjacent modules without any additional interactions or impacts when the PTO is running. In particular, windings terminal orientation, defining the rest of electrical connections, shall be specifically considered and designed with caution, looking for easy to access positions as separate as possible from the nearest mechanical element.

5.4 Interfaces between modules

The interface between modules shall guarantee the secure and safe operation of the complete machine without interacting with any active unit or conversion efficiency. They need to provide support and stiffness for the solution, acting as a locking mechanism between modules.

Therefore, all fixation elements should be designed to be a perfect fit and vibration resistant, this to ensure tightness of the PTO during the operation period.

5.5 Energy chain and flexible cabling.

Some MC PTO configurations requires the inclusion of energy chain and flexible cabling because of the active part (windings) moving inside or outside the stator. The following recommendations should be noted when deciding about this particular element:

- Cable weight: Energy chains may be designed for self-supporting when below some weight limits. If the required cabling and connectors surpass said limits some additional interface or supports shall be considered.

- Bend radius: PTO housing needs to consider the bend radius of the energy chain; smaller bend radius may affect the life cycle of the energy chain. Energy chains bend radius may punctually raise because of its operation principle, it should be considered a 15 % security margin over the design radius or additional support interfaces.

5.6 Communication protocols

The communications protocol used with the WEC power take-off system between the various components and sub-systems is of critical importance. Each PTO topology may be different, but all will share the same core functionalities. As such, a common definition of communication protocol, variable addresses, and data types will be beneficial to the integration of WEC subsystems of different origins.

The communications protocol between the High-level control system and the Low-level (power electronics level) controller is the highest priority interface for standardization due to the high likelihood of these two systems being separately developed in different companies or by different engineering teams. Elsewhere, the communication protocol between power electronics modules and the low-level control may be a standalone unit developed as a single system without the need for standardization or any external interfacing.

5.7 Other relevant components to consider

5.7.1 General

In this section some relevant components are analyzed although they cannot be considered as interfaces of a given MC PTO solution.

5.7.2 Bearings and rolling guides

A series of bearings shall be positioned along any of the modular units (translator and/or stator) relative to the desired motion of the translator and resting over the rolling guides placed in the opposite modular unit. Bearings interface guides the translator modular unit while reducing friction and associated mechanical force dissipation (heat). Depending on the overall design of the PTO, bearings can be found only for one modular unit or both.

5.7.3 Heating/cooling unit

Depending on the heat loss study performed for the PTO, a heating/cooling unit might be required to ensure optimal working conditions (temperature, humidity) inside the PTO machine room.

Given the harsh and varying outdoor conditions (air temperature, water temperature, humidity, salinity), certain point require attention in the design of the heating/cooling unit:

- Closed circuit heating/cooling through a split system with an outdoor offshore-proof condenser.
- Acceptable temperature range within the PTO.
- Acceptable humidity range within PTO.
- Moisture separator required.
- Dust, sand & salt filter required.

Furthermore, attention must be paid to the design of the overall unit, and more specifically the configuration of the air inlet and the accompanying seal to keep water out.

Annex A
(informative)

Application case: SEA TITAN MC PTO

A.1 General

Here, SEA-TITAN PTO is to be found as an example of implementation for the recommendations presented along this document. The PTO solution is developed as part of the H2020 project with reference number 764014 with the objective of designing, building, testing and validating a modular and crosscutting Direct Drive PTO solution to be used with multiple types of WECs. Additional information about the project and current status can be found in www.seatitan.eu.

A.2 Translator modular unit

A.2.1 General

Active unit shorter than stator core unit and mounted inside it. For SEA TITAN solution, coils (Copper) are winded around an electrical steel core (940-100A) and supported by a non-conductive stainless-steel (AISI 304) star structure. Interfaces in Table A.1.

The active modular unit is defined and composed by 3 phases, 8 coils per phase for a total of 24 coils, 6 support star structures and interfaces. A total of 2 active units can be found, one acting as a generator and the other acting as a motor, or actuator, providing a directly coupled back-to-back solution for laboratory testing.

Table A.1 — Sea Titan translator interfaces

Interface	Type	Between	Description
Bearings (Stud type track rollers)	Mechanical	Active - Passive	Resting over the rolling guides allowing the linear movement of the active part inside of the passive part.
Electrical connectors, flexible cabling and energy chain	Electrical	Stator – Power electronics	Responsible of the cable routing, connection and movement between elements.

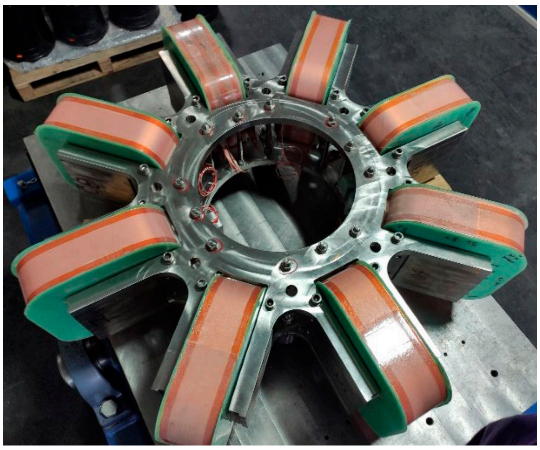

Figure A.1 — PTO translator, active modular unit

A.2.2 Stud type track rollers: NUKRE40

Principle of operation: Bearings constrains relative motion between part to only linear movement and reduces friction between moving parts.

NUKRE40 has been tested for good results in real environment. This model is suggested to guarantee the security of the complete solution. Alternative solutions should consider Axial guidance with eccentric collar, labyrinth seals on both sides. 96 units per active module.

D (mm)	**De** (mm)	**B** (mm)	**Mass** (g)	**Speed** (rpm)	**Fatigue limit** (N)
40	22	58	258	550	3 250

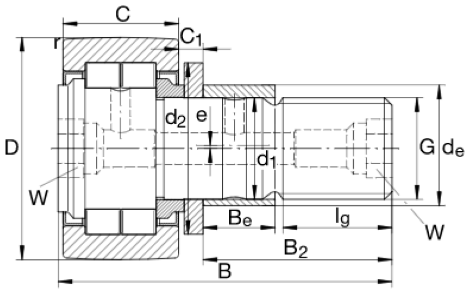

Figure A.2 — NUKRE40

A.2.3 Electrical connectors, flexible cabling and energy chain

SEA TITAN MC PTO attends to configuration 4 (Figure A.1). For that reason, energy chain (IGUS E4.1L) and flexible cabling (IGUS chainflex) are required. Weights are below the self-supporting limit, additionally, to avoid bending radius punctually rising an energy chain support is installed along all of the chain length.

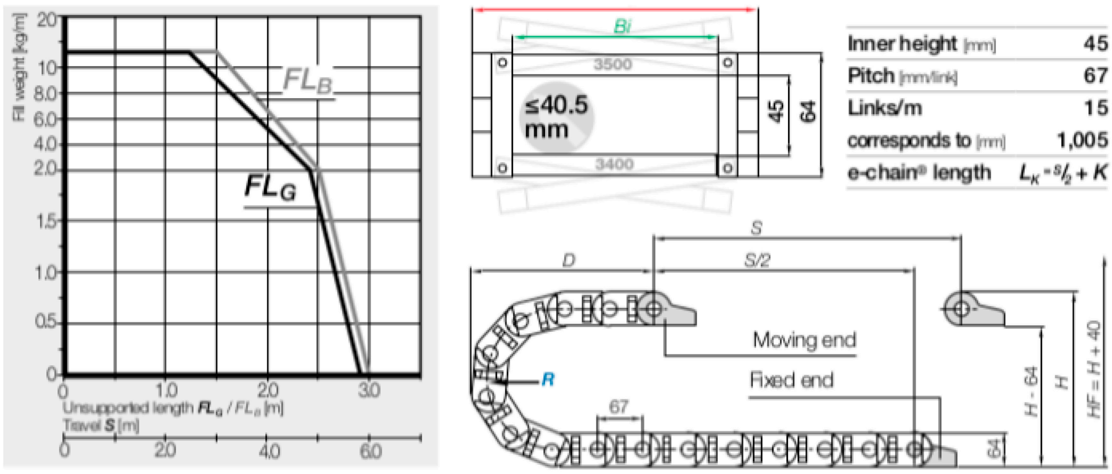

Figure A.3 — SEA TITAN MC PTO – Energy chain

A.3 Stator modular unit

A.3.1 General

SEA TITAN MC PTO is defined by the passive cores as modular unit (Figure A.5-right), made in electrical steel laminations (940-100A), support rings made in non-alloy steel (EN 1.0420), mechanical and electrical interfaces. A total of fifteen stator modular units are present to match the two translator modular units.

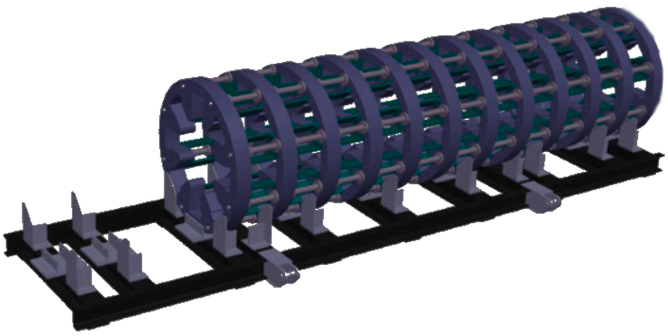

Figure A.4 — SEA-TITAN linear generator – Stator 3D model, partly mounted

Four relevant interfaces can be found:

Interface	Type	Between	Description
Rolling guides	Mechanical	Translator – Stator	Guide for the bearings present in the active part.
Main frame insulation & locking	Mechanical	Primary structure – Stator	Prototype for laboratory testing. No insulation. Main frame designed to sit the PTO on laboratory floor.
Mechanical bolts	Mechanical	Stator modular units	Bolts between stator modular units to guarantee stator stiffness and linear guidance.

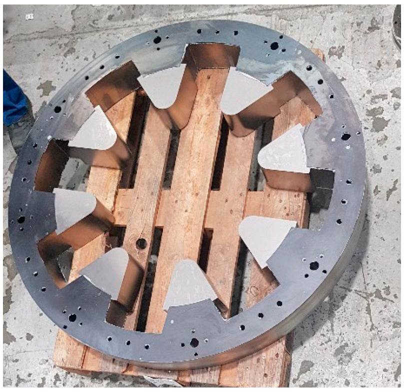

Figure A.5 — PTO Stator modular unit: support ring and cores

A.3.2 Rolling Guides

Bolted on the stator, with some additional interfaces for alignment and stiffness purposes, it provides support and guidance for the bearings present in the translator. The modular PTO requires a total of 16 guiding lines matching the active bearings, each one composed by the required number of rolling guide unit to cover the stator from side to side.

A.3.3 Main frame

Designed to allow the generator to sit on the laboratory floor and easy manipulation for road transportation, loading and unloading. Material is cast non-alloy Steel (EN 1.0420). Stator modular units are supported and bolted to the main frame. The main frame does not include any kind of integrated damping material between the floor and the structure, but it will be implemented as damping pad mat solution, commercially available.

Figure A.6 — SEA TITAN MC PTO – Main frame, 3D model

A.3.4 Mechanical bolts

Designed as interface between stator modular units (passive poles), providing stiffness to the PTO. Material is cast non-alloy Steel (EN 1.0420). Stator modular units are supported and bolted to the main frame individually and mechanically bolted between them.