Generic WEC System Breakdown

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Document Number: NA

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1 Objectives
This report is the deliverable 5.1 of SDWED project. The main objective of this deliverable is to provide generic and systematic WEC system breakdown. The generic system break down will be one of the bases for generic risk ranking and failure mode analysis which is required for overall reliability assessment of the WECs. Moreover systematic break down shed light on a possible way for classification of the WECs.

2 Introduction
WEC technology is still on its way to reach commercialization state with several challenges remaining to be solved. The main challenges for WEC developments are reliability and cost and all WEC developers are working to find the practical balance between these two parameters. As a result numerous patents, inventions and innovations have been created in an attempt to solve the mentioned challenges which create huge diversity of WECs types. According to [1] there are near 85 active WEC developers globally and according to [2] over 1000 wave energy conversion techniques are patented in Japan, North America and Europe.

Despite the diversity, WECs can be broken down in few common discrete subsystems as it is demonstrated in Figure 1 which is inspired from [3]. From this it was apparent that the variations of WECs design are mostly due to variation in Hydrodynamic, Reaction and PTO Subsystems while the other subsystems are fairly standards for all WECs.

For a purpose of classification the variation between PTO can be ignored since it doesn’t fundamentally change the WECs characteristics. Combination of Hydrodynamic and Reaction Subsystems were used to group the different WEC machine and categorize them as it is shown in Table 5.

3 Generic WEC Technology Assessment
There exists a very wide variety in the range of existing WEC devices. In this exercise, listing every possible component would be clumsy and defeat the purpose of the assignment, as it would render the work unusable. In order to have a manageable system breakdown, the following description adopts a high level breakdown that is able to be further refined adopting modular approach. The aim of the latter is to breakdown the system into recurrent elements, in order to group together similar components and keep the output of the exercise manageable for the end user.

The first high level breakdown is mostly adopted from [3] and is based on the main functions a WEC has to fulfil, as described below:
- Capture energy from the waves
- Convert wave energy into grid quality electricity
- Transfer energy to the shore
- Withstand environmental conditions
- Remain at a defined geographical location

The analysis of the above functions, along with a review of the existing technologies resulted in the high level breakdown shown in Figure 1. The WEC is divided into 5 major subsystems. Interface blocks (in yellow) represent system boundaries. For a better understanding of the interaction between subsystems, interactions between blocks are colour coded. Black represents environmental loading such as wave, current and wind. Purple shows exchange of force, moment and motion, red is for a flow of command signals from the instrumentation block towards other systems while blue depicts sensor measurement signals from other systems towards the instrumentation blocks.

The Hydrodynamic Subsystem interacts with the waves in order to capture their energy. Mechanical energy in the Hydrodynamic Subsystems passes to the PTO and the Reaction Subsystem in the form of force and motions. The PTO converts absorbed mechanical energy into grid quality electricity while the Power Transmission Subsystem transports it to the grid. The reaction subsystem maintains the position of the WEC by interacting with seabed and environment. The instrumentation and control subsystem measures all required information from other subsystems and sends appropriate command signal to ensure safe and reliable operation in all conditions.

Every WEC design can be broken down to fit in this generic high level description. This can be seen as common platform for the establishment of generic FMEAs for WECs.

![Figure 1: Typical WEC block diagram](image-url)
Before further describing each block, a partial conclusion can be drawn from this initial work. The larger variety across the range of designs stems from the diversity in hydrodynamic subsystems and reaction systems, and in the way they are combined. For this reason, two different approaches have been adopted in the remainder of the work.

**a) Approach 1: Hydrodynamic and Reaction subsystems**

1. The description of the reaction and hydrodynamic subsystems was further refined into two lists of general concepts. Six different types of Reaction systems were found relevant to the WEC industry and here they are tagged as RS-1 to RS-6, and six different hydrodynamic system types were considered and tagged as HS-1 to HS-6. While this covers the larger part of the industry, DNV recognise that not every existing WEC will fit into this mapping of the industry. However, when a device is found not to be covered, DNV believe that at least part of its constitutive systems will be covered by this exercise.

2. The elements of the lists were then coupled, and it was found that all combinations are viable although some may be impractical. These combinations later on will be described in detail in 3.3

3. Groups of associations that were similar enough to be broken down together were formed. The grouping was based on the level of similarity of the constitutive components of each combination. The different groups will be further described in section 3.3

4. Each group was further broken down into its constitutive elements. The level of detail was chosen in order to maintain a good balance between the genericity of the exercise and the need for detail for the subsequent risk assessment to be meaningful.

Keeping the process generic and manageable was the main challenge. This approach can at first glance seem to go against the genericity of the process, as it involves specification of the hydrodynamic and reaction systems. However, it was found necessary, as it puts the breakdown of the different constitutive systems of a WEC into the context of a more global system. This allows the end user to draw a picture of the system that is being addressed, and therefore renders the exercise meaningful and manageable. Under the assumption that the initial lists of concepts provide an acceptable level of comprehensiveness, this approach provides a systematic way to cover a great range of WEC designs.

**b) Approach 2: Other subsystems**

The PTO, Energy Transmission, Instrumentation and Control subsystems are more standard and self-contained. They are more likely to be composed of off-the-shelf items, and they show less diversity.

As a consequence, these subsystems were addressed independently from the global system they may be implemented in (e.g. independently from the other subsystems represented in Figure 1). They are seen as self-contained blocks.

**3.1 Hydrodynamic Subsystem**

The main function of this subsystem is capturing wave energy in the efficient manner. It actively transfers its motions and forces to both Reaction and PTO subsystems. Several types
of Hydrodynamic Subsystems exist. For the purpose of this exercise, they have been
categorised on the basis of their action principles:

- Oscillating body: An oscillating body is a rigid body or combination of rigid bodies with relative
degrees of freedom which oscillate by wave excitation force. Oscillating hydrodynamic systems
can either be single body, multi body systems as it was mentioned. (the PTO capturing energy
from the relative motion of the bodies)

- Oscillating water column: An oscillating water column device uses the rising and falling of the
water surface inside a closed cavity to push a fluid through a turbine. This fluid in most cases is
air but for DRAKOO WEC the fluid is seawater.

- Overtopping device: Overtopping devices convert wave energy into potential energy by causing
incoming waves to overtop into a reservoir. The potential energy of the stored water is then
used to rotate a turbine

- Diaphragm pressure differential: These devices use the pressure field created by incoming waves
on a flexible membrane to create pressure waves in a closed chamber, and rotate a turbine.

At present, the oscillating body category is the one that presents the largest diversity in the
industry. There are different action principles within this division, and they have implications
on the way the PTO is arranged and connected to other systems, and on the reaction systems
they can be associated with. For this reason, it was decided to break this group down into
three subcategories:

- Systems mainly extracting energy from their heaving motion
- Systems mainly extracting energy from their pitching motions
- Systems extracting energy by exploiting more than one degrees of freedom

The list of concepts for the hydrodynamic subsystem is shown in Table 1.

Table 1: Hydrodynamic Subsystem categorization

<table>
<thead>
<tr>
<th>Hydrodynamic subsystem description</th>
<th>Oscillating body</th>
<th>Overtopping</th>
<th>Oscillating water column</th>
<th>Diaphragm pressure differential</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heave</td>
<td>Pitch</td>
<td>More than 1 mode of motion</td>
<td>HS11</td>
<td>HS12</td>
</tr>
</tbody>
</table>

3.2 Reaction Subsystem

The main function of the Reaction subsystem is to maintain the position of the WEC and
transfer loads to the seabed. This will be described in section 3.3.

The first level of categorisation is based on the structural nature of the system. It can be
attaching the hydrodynamic subsystem to the seabed in a compliant manner, or in a rigid
manner. The reason for this separation is that each category presents distinct failure modes,
and implies different depth of installation. A compliant reaction system is more likely to be
used in deep water (offshore), whereas a rigid reaction system is more likely to be use in
taller water (nearshore).

3.2.1 Compliant reaction systems

Compliant reaction systems are at least composed of mooring lines (further called position
keeping system) and an anchoring system (here in called foundation system). The different
configurations are illustrated in Table 3.

Foreseeing the subsequent risk assessment, this group has been broken down into single line
reaction systems and multiple-line reaction systems. This is because the failure of a line has a
greater consequence if there is no redundancy in the position keeping system. A mooring
system is called single line where at least one of the lines of the arrangement does not have
redundancy. A mooring is called multiple-line if every line has some degree of redundancy in
the mooring arrangement.

Within these divisions, the mooring systems have been separated according to whether they
are slack mooring systems, taut mooring systems, or a combination of slack lines and taut
lines (combined configuration). The justification for this division is that taut mooring systems
are not compatible with every hydrodynamic system, as they can restrict their motions and
reduce their energy capture. This is particularly relevant to HS12 and HS13.

Combined configuration reaction systems (RS1130 and RS122X) include one or several
floating bodies in their position keeping mechanism, making the junction between lines
fulfilling different functions. The float is usually used as a stiffener in the mooring system,
increasing the tension in the lower line(s), whereas the higher lines allow for a certain degree
of freedom to the moored structure.

For multi-line configurations, the nature of the attachment of the lines onto the moored
structure was also highlighted. It can be either
- a multi-point attachment, or
- a single point attachment.

This is an important feature to take into account, as when it is linked up to the geometrical
properties of the hydrodynamic system, it determines the directionality of the system, that is
to say whether the device energy absorption capacity is sensitive to the direction of incoming
waves or not. Table 2 details the different combinations, and their impact on the directionality
of the system.
Table 2: Combination of the Hydrodynamic geometries and number of attachment points and effect of them on directionality

<table>
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<th>Type of mooring</th>
<th>Geometry of the float</th>
<th>Axisymmetric</th>
<th>Asymmetric</th>
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<tr>
<td>Single line</td>
<td>Slack line</td>
<td>NON DIRECTIONAL</td>
<td>NON DIRECTIONAL</td>
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<td></td>
<td>Taut line</td>
<td>NON DIRECTIONAL</td>
<td>CAN BE DIRECTIONAL</td>
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<td>Multi line</td>
<td>Single point attachment</td>
<td>NON DIRECTIONAL</td>
<td>CAN BE DIRECTIONAL</td>
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<td>Multi point attachment</td>
<td>NON DIRECTIONAL</td>
<td>DIRECTIONAL</td>
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Table 2 shows that combining an asymmetric hydrodynamic system with a multi-point attachment mooring system results in a directional system, meaning that the WEC is only able to capture energy from a restricted wave direction. This can also be the case when combining an asymmetric hydraulic subsystem when a single taut line.

A compliant reaction system can also include:

- **Support Structure**: It is generally a stable structure, which can either be floating or submerged. It is used as a reaction point for the PTO, and/or as a platform to support hydrodynamic system(s).

- **Height adjusting mechanism**: It allows the control of the tension in the mooring lines and the draft of the hydrodynamic system, during operation or installation. This can for instance consist of a winch mechanism.
### Table 3: Compliant reaction subsystem categorization

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3.2.2 Rigid reaction systems
The different configurations are illustrated in Table 4. Rigid reaction systems can either be elevated, e.g. the attachment point of the hydrodynamic system is raised to be close to the surface or strictly on the bottom.
The latter is especially relevant for WECs that are reacted directly on the seabed through their PTO. Possible examples are
- An oscillating water column located on the shore line such as LIMPET WEC.
- A pitching oscillating body that would be directly reacted onto the seabed through its PTO such as Oyster WEC.
- A heaving oscillating body that would be directly reacted onto the seabed through its PTO such as CETO.

In these cases, the reaction subsystem would consist in the foundations and potentially a support structure, which would be located directly on the seabed, providing support to the PTO(s), and possibly to the control system, or to other subsystems. The latter example is not to be mistaken with a single taut mooring line, which does not provide reaction through the PTO.
Elevated reactions systems come in two types:
- The jacket type
- The column type

The second type can be considered with single column and multi column. The consequence of failure of a single column is more severe than a multi column.
Elevated reaction systems include at least an elevating structure (column or jacket), called position keeping mechanism, and foundations. They also commonly include a support structure, providing reaction and/or housing to the PTO. The position keeping mechanism can also include:
- A height adjustment system, which can for instance consist of a jack-up mechanism or a chain and winch mechanism (see section 3.3).
- An alignment mechanism, allowing the hydrodynamic system to adjust its orientation to the wave direction. For the purpose of this exercise, it was decided that only passive alignment mechanisms would be considered, e.g. mechanisms that are not powered, and that do not require a locking mechanism to maintain the hydrodynamic system into the desirable direction.
Table 4: Rigid reaction subsystem categorization

<table>
<thead>
<tr>
<th>Rigidly fixed to the seabed</th>
<th>RS2110</th>
<th>RS2120</th>
<th>RS2130</th>
<th>RS2200</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elevated Jacket RS2110</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Single Column RS2120</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Multi Columns RS2130</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bottom height RS2200</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

3.3 Hydrodynamic and Reaction subsystems association

As mentioned in 3 approach 1, the combinations between the different hydrodynamic and reaction subsystems were assessed and grouped together to form categories of WECs. Converters within the same category have similar arrangements between reaction and hydrodynamic systems, and can thus be broken down together.

Table 5 shows the different associations and groups that were built.
### Table 5: Combination of HS & RS

<table>
<thead>
<tr>
<th>Compliant</th>
<th>Multiple line</th>
<th>Rigidly fixed to the seabed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Taut</td>
<td>Slack</td>
<td>Combined configuration</td>
</tr>
<tr>
<td>Single line</td>
<td></td>
<td>Single attachment</td>
</tr>
<tr>
<td>Slack</td>
<td>Taut</td>
<td>Multi attachment</td>
</tr>
<tr>
<td>Combined</td>
<td>Slack</td>
<td>Single attachment</td>
</tr>
<tr>
<td>configuration</td>
<td>Taut</td>
<td>Multi attachment</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Single attachment</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Multi attachment</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Elevation</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Height</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Rigidly fixed to the seabed</td>
</tr>
</tbody>
</table>

#### Compliant
- **Heave**: HS11
- **Pitch/Roll**: HS12
- **Overtopping**: HS20
- **Oscillating Water Column**: HS30
- **Diaphragm**: HS40

#### Multiple line
- **Slack**: RS11, RS12, RS20
- **Combined configuration**: RS13, RS21

#### Rigidly fixed to the seabed
- **Jacket**: RS1110, RS1120, RS1130
- **Single Column**: RS1211, RS1221, RS1231
- **Multi Columns**: RS1212, RS1222, RS1232

**Types**
- **Type 1**: Oscillating body
- **Type 2**: More than one degree of freedom
- **Type 3**: Pitch/Roll
- **Type 4**: Overtopping
- **Type 5**: Oscillating Water Column
- **Type 6**: Diaphragm
- **Type 7**: Compliant
- **Type 8**: Rigidly fixed to the seabed
3.3.1 Type 1

Type 1 groups together all offshore oscillating bodies. It is implied here that the PTO, and hence the motion of the hydrodynamic system is not directly reacted onto the seabed, but that the reaction is made onto a large supporting structure (reference is made here to the description of the support structure made in section 3.2.1). This structure can give support to one or several hydrodynamic systems, and is reacted onto the seabed through a mooring line arrangement, and ultimately through its foundations. Figure 2 illustrates Type 1 WECs schematically.

The breakdown of Type 1 WECs is given in APPENDIX A.

Most elements of the breakdown are either described in sections 3.1 and 3.2.1, or do not need further explanation as they are fully understood by the industry. Further description is given here where specific additional assumptions are made regarding the Type 1 arrangement.

- **Support structure**

As mentioned above, this structure provides reaction to one or several PTO(s) and/or Hydrodynamic subsystems and can be either floating or submerged. It is directly in the load-path between the hydrodynamic subsystem and the foundations, and therefore its structure is designed to withstand environmental and structural loads.

Part of the PTO may be enclosed inside the support structure, for this reason water-tight cavities were included in the breakdown. The structure may also comprise permanently flooded cavities in order to increase its weight, or ballasts to regulate it.

- **Position keeping mechanism**

The following attachments between the mooring lines and the support structure have been considered:

- The attachment allows full rotation in Yaw direction using i.e. swivel or turret.
- The attachment does not allow full rotation in yaw direction. It provides only small compliance in yaw direction due to torsional stiffness of the line.

- **Hydrodynamic system**
It is assumed that the hydrodynamic can include a passive alignment mechanism, that is to say, its hydrodynamic features allow it to align with the optimal direction to maximise the energy capture.

As the support structure, it can comprise flooded cavities, Water tight cavities and ballasts.

It is highlighted in the breakdown that the hydrodynamic system can be attached to the PTO through a tether (that is to say a taut line). It is important to emphasise that in this case, this tether is not part of the reaction system, but part of the interface between the hydrodynamic system and the PTO.

### 3.3.2 Type 2

Type two is the subgroup of Type 1 with future of not having support structure. These bodies are commonly either pitching or using more than one degree of freedom to capture energy, the good example here is Pelamis WEC. Figure 3 illustrates Type 2 WECs schematically.

![Figure 3: Type 2 WEC schematic](image)

As mentioned Type 2 WECs do not need a reacting structure to operate, and as a consequence, they cannot use taut mooring systems, as it would restrict their motions and reduce their energy capture.

Hydrodynamic systems of Type 2 WECs can either be self-contained bodies, or multi-body systems. A hydrodynamic system is called multi body when it is composed of two or more bodies directly interacting with the waves.

Other assumptions on reacting hydrodynamic systems are described in 3.3.1.

The breakdown of Type 2 WECs is given in APPENDIX B.

### 3.3.3 Type 3

Type 3 WECs are oscillating bodies mounted on rigid elevated position keeping mechanisms. Figure 4 illustrates Type 3 WECs schematically.
This type of WEC is more likely to be used nearshore, as rigid reaction systems present a number of advantages for shallow water locations.

Most assumptions and components have been described in section 3.1, 3.3.1, and 3.2.2.

WECs belonging to this category commonly have a support structure housing the PTO system and providing attachment to the hydrodynamic system. However, when column(s) are used as a position keeping mechanism, they can also play the role of providing housing to the PTO system. For this reason columns can comprise watertight cavities. Columns can also be filled with seawater or concrete.

Type 3 WEC can be fitted with a height adjustment mechanism. This can be either
- A rack and pinion mechanism,
- A pin and hole mechanism or
- A chain and winch mechanism.

These mechanisms can be used during operation, to accommodate for the water level, or during installation, where the WEC would be floated out and then jacked up in position.

The breakdown of Type3 WECs is given in APPENDIX C.

### 3.3.4 Type 4 and Type 5

Type 4 and type 5 WECs are oscillating bodies directly reacted onto the seabed through their foundations. They do not include position keeping mechanism as defined in section 3.3.2. As mentioned in section 3.2.2, WECs belonging to this category possibly comprise a support structure, but as opposed to other types of WEC, it is directly located onto the seabed.

Type 4 WECs the reaction of the Hydrodynamic Subsystem is solely made through the PTO, the good example for this category is CETO WEC. It follows that for this category of devices, the hydrodynamic system cannot be directly located and attached at seabed level, but rather higher in the water column, with the PTO(s) located directly between the hydrodynamic system and the foundations, or possibly the support structure. Figure 5 illustrates Type 4 WECs schematically.
As opposed to type 4, Type 5 hydrodynamic systems are located and attached directly at seabed level. Figure 6 illustrates Type 5 WECs with a principle diagram.

The breakdowns of Type 4 and Type 5 WECs are given in APPENDIX D and APPENDIX E respectively.

### 3.3.5 Type 6, Type 7 and Type 8

These types of WEC differ from the previous ones in that their hydrodynamic systems are not oscillating bodies. They are rigidly fixed onto a large support structure.

The support structure is a large body providing reaction and attachment to one or several PTO(s) and/or Hydrodynamic subsystems. It can be floating in case of a Type 6 WEC, or rigidly fixed in case of a WEC of type 7 or 8. Its structure is designed to withstand environmental and structural loads.

For Type 6 WECs, the assumptions made on the reacting subsystem are similar to those made for Type 1 WECs.

For Type 7 WECs, the assumptions made on the reacting subsystem are similar to those made for Type 3 WECs.

The Hydrodynamic subsystem is divided into two parts:
- The extracting mechanism is the part that absorbs the energy from the waves.
- The focusing mechanism is the mechanism that interacts with the incoming waves prior to the energy conversion, in order to make the wave energy converge towards the extracting mechanism and maximise the conversion. It usually comes in the form of focusing arms, which geometry can be adjusted according to the wave conditions. Figure 7 and Figure 8 schematically show type 6 and type 7 WECs.

Type 8 WECs are likely to be positioned on the shoreline, as they do not comprise a position keeping mechanism as defined in 3.2.2. Their support structure directly rests on the seabed. Figure 9 shows a type 8 WEC schematically.

The breakdowns of Type 6, Type 7 and Type 8 WECs are given in APPENDIX F, APPENDIX G and APPENDIX H respectively.

### 3.4 PTO Subsystem

PTO converts captured wave energy, into the grid quality electricity. There are few exceptions in which the PTO doesn’t generate grid quality electricity such as desalination and autonomous WECs. In the case of desalination, PTO pumps the sea water through membrane for production of potable water hence there is no generation of electrical power. In the case of autonomous WECs, the produced electricity can be in any form depending on load...
requirement. For instance, the autonomous WEC may be utilized to produce DC electricity for running a specific type of instrument.

The basic operation starts with transferring motion and force of the Hydrodynamic Subsystem to the generator shaft. Several types of PTO mechanisms can be used for this purpose. These are listed in Table 8 and tagged from PS1 to PS7. The PS1 to PS6 are suitable for oscillating body while the turbine (PS7) is commonly used in the other type of Hydrodynamic Subsystem such as OWC or overtopping.

- **Hydraulic PTO**: In the hydraulic PTO the cyclic motion of the HS causes the linear actuator (Hydraulic cylinder) to move back and forward. The reciprocating motion of the actuator pumps the fluid through the hydraulic system. A specific arrangement of valves and accumulators controls and diverts the fluid to the Hydraulic motor which rotates the generator shaft. It should be noted that in some WEC designs part of the Hydraulic system is onshore so there is subsea piping to connect the linear actuator to the hydraulic motor and this subsea pipe line should not be seen as a part of power transmission subsystem but as part of PTO subsystem.

The hydraulic system typically consists of the components which are listed in Table 6.

<table>
<thead>
<tr>
<th>#</th>
<th>Components</th>
<th>Example and description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Valves</td>
<td>Control flow, pressure and direction. Such as relief valve.</td>
</tr>
<tr>
<td>2</td>
<td>Motors</td>
<td>Converts fluid power to linear or rotary mechanical motion. Such as Vane motor.</td>
</tr>
<tr>
<td>3</td>
<td>Pumps</td>
<td>Converts rotary or linear mechanical power to fluid power. Such as Fix or variable displacement piston pump.</td>
</tr>
<tr>
<td>4</td>
<td>Fluid Conditioning</td>
<td>Condition the fluid characteristics such filters, heaters and heat exchangers.</td>
</tr>
<tr>
<td>5</td>
<td>Fluid Connectors</td>
<td>Connects different fluid power components. Such as Pipe, Manifolds, Hose and Hydraulic connectors.</td>
</tr>
<tr>
<td>6</td>
<td>Fluid</td>
<td>It is a fluid in the system. Such as water base or oil base media.</td>
</tr>
<tr>
<td>7</td>
<td>Accumulators</td>
<td>It is storing the potential fluid power. Such as bladder or piston accumulator.</td>
</tr>
</tbody>
</table>

- **Pneumatic system**: Pneumatic system is similar to the Hydraulic system. Here the media is air rather than the liquid which makes the system less stiff. Typical Pneumatic components are listed in Table 7.

<table>
<thead>
<tr>
<th>#</th>
<th>Components</th>
<th>Example and description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Valves</td>
<td>Control flow, pressure and direction. Such as reducer valve.</td>
</tr>
<tr>
<td>2</td>
<td>Motors</td>
<td>Converts Pneumatic power to linear or rotary mechanical motion. Such as Air turbine.</td>
</tr>
<tr>
<td>3</td>
<td>Compressors</td>
<td>Converts rotary or linear mechanical power to pneumatic power. Such as double stage or screw compressor.</td>
</tr>
<tr>
<td>4</td>
<td>Fluid Conditioning</td>
<td>Condition the air characteristics such filters, dryer, oiler and silencer.</td>
</tr>
</tbody>
</table>
5 Fluid Connectors
Connects different pneumatic components. Such as Pipe, Manifolds, Hose and Hydraulic connectors.

6 Fluid
Usually media is air but in some cases can be pure nitrogen.

7 Reservoirs
It is storing the potential pneumatic power.

- **Rack & Pinion**: In Rack & Pinion PTO the cyclic motion of the HS causes the Rack Gear to move back and forth. The rack motion must be constrained to only move in axial direction. Reciprocating motion of Rack Gear causes the rotation of the Pinion gear which rotates generator shaft. This system consists of Rack Beam, Rack Gear, Pinion and Pinion bearing assemblies.

- **Ball Screw**: This PTO exploit ball screw mechanism to convert linear motion to rotary motion for turning the generator shaft. One end of the Screw is connected to HS which force the screw to move. The motion of the Screw must be constrained to only axial direction. The screw nut is free to rotate but constrained in axial direction by using thrust bearing. Linear motion of the screw forces the nut to spin. Coupling of the nut rotation to the generator shaft can be done by using the worm gear arrangement. The schematic Ball Screw arrangement is shown in Table 8. Typical Ball Screw PTO is consisting of Screw, Screw Nuts, Bearing assemblies and Worm Gear assemblies.

- **Direct Drive**: This PTO directly employed electromagnetic phenomena for conversion of mechanical to electrical power. Simply moving magnet induced electricity to the coil.

- **Rope & Pulley**: This PTO exploits ropes and pulley mechanism for conversion of the linear motion to rotary. Generally speaking ropes transfer the loads only in tension mode and they are simply slack in compression. To overcome this problem extra provision is required to ensure that during the compression the rope remains in tension.

- **Turbine**: turbine is used in OWC, Diaphragm and overtopping HS types. The common type of turbine according to [4] are:
  - **Wells turbine**: It is a self-rectifying turbine. The airfoil is symmetric with respect to the rotation plane which allows turbine to rotate continuously in one direction in spite of the change in air flow direction. The Wells turbine can be single stage or multi stages with the vane guide.
  - **Impulse turbine**: It works by impulse of air on the bucket shape blade. It can be unidirectional or bidirectional.
  - **Dennis Auld turbine**: It is a variable pitch impulse turbine used which is used in Port Kembla OWC.
  - **Radial Turbines**: It is an Impulse turbine in which the air flow in radial direction in respect to the rotor shaft.
  - **Cross flow turbines**: In this turbine the air flows in traverse direction or across the turbine blades.
<table>
<thead>
<tr>
<th>#</th>
<th>Name</th>
<th>Description</th>
<th>Schematic Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>PS1</td>
<td>Hydraulic</td>
<td>Linear motion of cylinder causes high pressure liquid (Usually oil) flows through the manifolds. Manifolds direct the oil to the hydraulic motor and cause rotation of the motor. High pressure and low pressure accumulator are used for smoothing the operation and also supplying tank pressure.</td>
<td><img src="image" alt="Hydraulic Schematic" /></td>
</tr>
<tr>
<td>PS2</td>
<td>Pneumatic</td>
<td>Pneumatic PTO is similar to the Hydraulic one, except the media is air.</td>
<td><img src="image" alt="Pneumatic Schematic" /></td>
</tr>
<tr>
<td>PS3</td>
<td>Rack &amp; Pinion</td>
<td>Linear motion of the racks causes pinion to rotate.</td>
<td><img src="image" alt="Rack &amp; Pinion Schematic" /></td>
</tr>
<tr>
<td>PS4</td>
<td>Ball Screw</td>
<td>Linear motion of the screw causes the nut to turn. The outer side of the nuts has a gear profile which engaged with the worm gear shaft for 90 degree rotation of the rotation axis.</td>
<td><img src="image" alt="Ball Screw Schematic" /></td>
</tr>
<tr>
<td>PS5</td>
<td>Direct Drive</td>
<td>Motion of the magnet induces electricity into the coil.</td>
<td><img src="image" alt="Direct Drive Schematic" /></td>
</tr>
<tr>
<td>PS6</td>
<td>Rope &amp; Pulley</td>
<td>Linear motion of the rope rotates the winch hub.</td>
<td><img src="image" alt="Rope &amp; Pulley Schematic" /></td>
</tr>
<tr>
<td>PS7</td>
<td>Turbine</td>
<td>High pressure air/liquid flows through sets of blades which causes rotation of the turbine shaft.</td>
<td><img src="image" alt="Turbine Schematic" /></td>
</tr>
</tbody>
</table>

Production of electricity starts with rotation of the generator (In case of linear generator the motion is linear). Produced AC electricity has variable frequency and amplitude due to the nature of the wave motion. This electricity has to be converted to single frequency (Usually
50 or 60Hz) with fix amplitude. Converting random AC electricity to grid quality electricity is usually done by utilizing high power electrical drives. The method well established in wind industry and it consists of two drives working in series with the DC storage bank sitting in the middle. First drive converts random AC to DC (AC/DC convertors) and stores it in DC bank. The DC bank provides stable voltage source for the second drive which converts DC electricity to grid quality AC. Figure 10 shows this process schematically. There is need to handle excess energy production, in a case that the grid is down or the production of the electricity is more than delivery to the grid or there is requirement for slowing down the PTO. This can be done by dissipation of energy through the resistor bank sometimes known as brake resistors. This is shown schematically in Figure 11.

Successful operation of the PTO depends on several auxiliary subsystems. These subsystems maintain the operational condition in acceptable level for safe and reliable operation of the PTO. In the WEC breakdown these auxiliary system are seen as a part of PTO. Few examples of them are listed below:

- Brake/Latch System
- Shock Absorption System
- Heating/Cooling System
- Lubrication System
- Vacuum System
- Bilge System
- Air Treatment System
- Ballasting System
- Fire Fighting System
- Backup Power System (Batteries, Diesel generators...
Figure 12 shows the example of expanded PTO Subsystem in more detail considering necessary auxiliary and drive systems. As it can be seen two Auxiliary Subsystems (Brake and Cooling) provide critical service for reliable functionality of PTO. In this example it is assumed that the source of electrical power for running Auxiliary Subsystems is from outside the PTO, for instance from grid, while it is perfectly possible to source it from inside the PTO using Drive outputs in Generator and Drive block. It should be noted that some of Auxiliary subsystems may have interaction with Reaction or Hydrodynamic subsystem. The good example of this case is Ballasting System.

3.5 Instrumentation and control Subsystems

Instrumentation and control is the brain of the WEC. This subsystem deals with measurement and device control. Generic structure of this subsystem is shown in Figure 13 and major components are:

- **Sensors**: Measuring various parameters and data across the whole systems. They usually equipped with transducer which coverts physical quantity to the electrical signal. Base on their measurement criticality, they can be categorized in three groups as below:
  - Monitoring sensors are used for purpose of monitoring and learning of the machine behaviour.
  - Alarm sensors are used for alarming when a signal passes certain threshold.
  - Control sensors measurement values are constantly fed into the controller and process in real time for controlling the machine.

- **Data Acquisitions (DAQ)**: Conditioning, Analogue Digital Conversion (ADC) and storage of the data are the main functions of the DAQ. Conditioning is preparation of raw signal to the usable level for other components. The process involves one or more of the following steps:

- **Processors**: Digital or analogue signals can be manipulated by processor using arithmetic operation. The following equipment’s are commonly used for processing:
  - **IPC**: Industrial PC is rugged desktop style computer which is extremely resistant to vibration and acceleration. These PC with appropriate software are commonly used for automation and electromechanical process.
  - **FPGA**: Field Programmable Gate Array is a configurable circuit through hardware description language. They can perform complex digital computation by using logic gates and RAM blocks.
  - **PLC**: Programmable Logic Controller is an industrial digital computer which is commonly used for automation and electromechanical process.

- **Communication and data transfer**: communication can be through a wireless system such as:
  - **Radio Transmission**: This is known as VHF with frequency band of 150 to 174MHz.
  - **Cellular Transmission**: With the frequency band of 450MHz to 2.1GHz. The GSM, GPRS, 3G, 4G are good examples of this system.
  - **Wi-Fi**: With the frequency band of 2.4 to 5GHz
  - **Sonar**: Sonar wave can be used for under water wireless communication such as transferring ADCP data to the WEC.
  - **Satellite**: In this method the transmission to the shore is done through the satellite so the range limitation can be improved. The good examples are INMARSAT, Iridium satellite system.

The most practical way of communication for WECs is through wire. The shore to WECs communication can be done via fibre optic while internal communication between WECs components can be done through Ethernet cable.

- **Human Machine Interface System (HMI)**: This is a part of a controller which handles the human interaction with machine. Keyboards touch screens, monitors, switches and joysticks are examples of HMI components which operators can work with.

![Figure 13: Generic structure of Instrumentation and Control](image-url)
3.6 Power Transmission Subsystem
The main function of this subsystem is transferring electrical power in an efficient and reliable manner from WEC to the grid or consumption source. It consists of high power electrical equipment, such as transformers, switchboards, switchgears, connectors and power cables.
AC transmission is the most common form of transmission nowadays but, High voltage DC (HDC) transmission is becoming more popular because it offers higher efficiency. Main difficulties with HDC are reliability and more frequent preventive maintenance regime requirement compared to AC transmission.

3.7 Interface Subsystem
As it was depicted in Figure 1, the hand shake between various subsystems is defined by interfaces. Theoretically almost any components can be seen as an interface depends on how one defines the system boundaries but one should be pragmatic about them in order to have traceable system breakdown. Here the most common interfaces are discussed.

3.7.1 Corrosion protections
Here Corrosion protection is seen as an interface between environment and the target material and as the name suggests it protects the target material from corrosion. Several methods have been developed for corrosion protection and each has its merit and demerit. Cost, compatibility and endurance are parameters which need to be considered for corrosion protection method selection. The corrosion protection can be categorized as it is shown in Figure 14.

- **Passive**: In this method the corrosion is prevented by isolating the target material from aggressive environment. The example of this type of protection are:
  - **Painting**: Applying pigmented coating materials in liquid, paste or in powder forms to the surface of target material which creates protective films and isolate the target material from the environment.
  - **Galvanization**: Applying protective Zinc layer to steel for corrosion protection.
- **Plating**: Applying very thin layer of protective metal such as Tin, Chrome, Nickel or Copper to the target material by using electro or electroless plating process.
- **Aluminium spraying**: Spraying a fine stream of molten aluminium on the surface of the target material.
- **Enamelling**: Applying powder glass to the surface of target material and then heat it up. The powder melts and then cools down to form smooth protective coating layer.

- **Active**: In this method the natural reaction process between environment and target material is disturbed by external influences. The example of this type of protection are:
  - **Cathodic Protection**: In this method the target metal is protected from corrosion by making it the cathode. The most common method is to use a sacrificial metal (known sacrificial anode) which corrodes and prevents the target metal from corrosion. In this method both sacrificial anode and the target metal must be submerged (electrolyte) to allow ionic current flow between cathode and anodes.
  - **Direct Current**: If the distance between anode and cathode is large or electrolyte resistance is high to allow flow of ionic currents, in this case it is possible to connect anodes and cathode to the source of DC power source and force the current between them.
  - **Dehumidification**: In this method desiccant bags or dehumidifier are used for reducing humidity of environment and preventing corrosion of the metallic surface due to oxidation.
  - **Ultrasonic**: In fact this system is used for antifouling rather than corrosion protection. In this method high frequency vibration induced to the structure using sonar. These vibrations prevent formation of marine growth and fouling.

### 3.7.2 Seals

Similar to corrosion protection, seals can be seen as an interface component. Seals are available in different shapes and materials.
Table 9 depicts a simple categorization of the seals based on their functionality.

The following material list for seals was adopted from [5]:

- Elastomers are cross-linked polymers that are capable of absorbing large reversible deformations. The good example is NBR.
- Thermoplastics are not cross linked high polymers. They can be permanently deformed under action of pressure and temperature. The good example is PTFE.
- Thermoplastic elastomer is produced similar to thermoplastics but they have high elastic properties. The good example is YSBR.
- Duroplastics are highly cross linked polymer materials are explained in detail in DIN 7724. The good example is PF.
- Metallic material is also used to produce gasket. These type of gasket usually used is mostly in petrochemical application.
Table 9: Seal Categorization

<table>
<thead>
<tr>
<th>Type</th>
<th>Type</th>
<th>Pictorial Example</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Static Seal</strong></td>
<td><strong>Axial</strong></td>
<td><img src="image" alt="Axial Seal" /></td>
</tr>
<tr>
<td>Where there is no relative motion between two components.</td>
<td>Where the seal is compressed in an axial direction</td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>Radial</strong></td>
<td><img src="image" alt="Radial Seal" /></td>
</tr>
<tr>
<td></td>
<td>Where the seals compress in radial direction</td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>Chamfer</strong></td>
<td><img src="image" alt="Chamfer Seal" /></td>
</tr>
<tr>
<td></td>
<td>Where the seal are compressed in both axial and radial direction.</td>
<td></td>
</tr>
<tr>
<td><strong>Dynamic Seal</strong></td>
<td><strong>Linear</strong></td>
<td><img src="image" alt="Linear Seal" /></td>
</tr>
<tr>
<td>Where there is a relative motion between two components.</td>
<td>Where there is linear motion between two components.</td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>Rotary</strong></td>
<td><img src="image" alt="Rotary Seal" /></td>
</tr>
<tr>
<td></td>
<td>Where there is rotary motion between two components.</td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>Bellows</strong></td>
<td><img src="image" alt="Bellows Seal" /></td>
</tr>
<tr>
<td></td>
<td>Where there is a requirement for elastic connection between two components.</td>
<td></td>
</tr>
</tbody>
</table>
3.7.3 Bearing

The function of bearing is to transfer the machine load safely between moving parts while minimizing friction and wear. The bearing classification presented here is mostly adopted from [6] and depicted in Figure 15.

- **Rolling Bearing:** These bearing are characterized by rolling motion between moving parts. These type of bearing are extensively use in machine design. This type of bearing less likely to be used between Hydrodynamic Subsystem and Reaction Subsystems because:
  1. High manufacturing cost
  2. Requirement for precision alignment which might impractical for large size bearing
  3. They are bulky compare to the type (Exclude the magnetic bearing)

- **Hydrodynamic bearing:** These bearing are sleeve bearing or an incline plain slider where a moving part floats on the thin film of the lubricant. The lift force, which floats the moving part, is generated by hydrodynamic pressure due to relative motion between moving part and fix part. These bearing are commonly used to connect HS to RS in WEC design. They are compact, simple and have less severe tolerance criteria. The hydrodynamic bearing may be divided to the following 4 self-explanatory categories:
  - **Rotary:** For Pitch/Roll motion this is very practical candidate. The good example is Oyster developed by AquaMarine. It also very extensively is used in mooring components such as spool.
  - **Spherical:** For using at the rod end of hydraulic cylinder to form a clevis point with limited rotary degree of freedom.
  - **Linear:** For Heave motion, the good example is PowerBuoy developed by OPT.
  - **Axial:** May be used in design of Turret or mooring line swivels.

- **Hydrostatic bearing:** In hydrostatic bearing the pressure in lubricant film is generated by an external pump. The pressure floats the moving part and separates it from fixed part. The advantage compared to Hydrodynamic bearing is that there is no dry start up. This type of bearing less common in WEC design because it requires extra accessories and adds complexity to the system.

- **Dry Bearing:** Advancement in polymer material such as PTFE or POM composite has led to creation of dry bearing. These bearing are lubricant free and can handle large forces at relatively high speed.

- **Magnetic:** In this bearing the loading capacity is generated by the magnetic field between moving parts. These bearing are used for unique application and are not common in WEC design. The cyclic and unpredictable nature of wave loading makes the magnetic bearing unsuitable for WEC design.
Figure 15: Bearing categorization
3.7.4 Connectors
Connectors is used as a general terms which connects different subsystems at interface points. It can be structural, mechanical or electrical.

4 WAVESTAR Case Study
In order to demonstrate how the described methodology for WEC breakdown can be applied to the existing systems, a case study was conducted for the WAVESTAR machine.

APPENDIX I shows how the machine fits in the high level breakdown shown in Figure 1. This breakdown is based on the documentation that was made available to DNV by Wave Star Energy A/S.

The approach presented in sections 3.2 to 3.7 was applied to the WAVESTAR machine. The device was found to be a Type 3 machine (see Table 5), composed of a pitching hydrodynamic system, (HS13) and a multi-column type elevated rigid reaction system (RS2130). APPENDIX J shows how the Type 3 HS & RS generic breakdown is applicable to the WAVESTAR machine. The components relevant to the system are highlighted in green. The WAVESTAR machine uses a hydraulic PTO, as described in section 3.4.

5 Reference


APPENDIX B  TYPE 2

Type 2
Offshore Pitch/Roll - Sway

RS

Position keeping system

Length adjustment system

Winches

See Type 3
Nearshore Fixed Oscillating

Single line

Combined configuration

Slack mooring

See Type 1
Offshore-Heaving

Multiple line

Combined configuration

Slack mooring

See Type 1
Offshore-Heaving

Mooring

See Type 1
Offshore-Heaving

Foundation

See Type 1
Offshore-Heaving

HS

See Type 3
Offshore-Heaving
## APPENDIX C  TYPE 3

**Type 3 Nearshore Fixed Oscillating**

<table>
<thead>
<tr>
<th>Component</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Structure</td>
<td>Nearshore fixed oscillating structure</td>
</tr>
<tr>
<td>Foundation</td>
<td>Foundation for the structure</td>
</tr>
<tr>
<td>Connection to HS/PTO</td>
<td>Connection to High Speed/Power Take Off</td>
</tr>
<tr>
<td>Support structure</td>
<td>Support structure for the foundation</td>
</tr>
<tr>
<td>Tower</td>
<td>Vertical support for the structure</td>
</tr>
</tbody>
</table>

### Support Structure Components

- Ornamented on PTO
- Bolted flange
- Swivel joint
- Sliding joint
- Universal joint

### Foundation Components

- Gravity base
- Driven pile
- Suction pile
- Drilled and grouted pile
- Penetration feet

### Connection to HS/PTO Components

- Hydraulic cylinder
- Chain and winch

### Support Structure Components

- Bolted flange
- Swivel joint
- Sliding joint

### Lifting System Components

- Hydraulic system
- Rack and pinion
- Pin and hole
- Gearbox

### Alignment Mechanism Components

- Clearance
- Universal joint
- Bolted flange
- Slewed joint
- Spool joint
- Connecting arm

### Position Keeping System Components

- Hydrodynamic appendices
- Clevis

### Type C Nearshore Fixed Oscillating Components

- Water tight cavities
- Flooded cavities
- Concrete filled structure

### Jacket Components

- Lifting system
- Weather tight cavity
- Ballasts

### Electrical Power Components

- Pin
- Local hole area
- Rack and pinion

### Hydraulic Power Components

- Rack
- Pinion
- Power

### See rack and pinion

- Gearbox
- Pin and hole
**APPENDIX D  TYPE 4**

**Type 4 Nearshore Heaving**

- **Foundation**
  - Suction pile
  - Driven pile
  - Drilled and grouted pile
  - Gravity base

- **RS**
  - Support structure
    - Waterproof cavity
    - Structure
      - Universal joint
      - Connection to PTO
      - Built in foundation
    - Swivel joint

- **HS**
  - See type 1 Offshore Heaving

See type 3 Nearshore Fixed Oscillating
Type 5 Nearshore Pitch/Roll

**RS**
- Foundation
- Structure
- Water proof cavity
- Alignment mechanism
- Connection to HS / PTO
- Swivel joint
- Universal joint
- Built in foundation

**HS**
- See Type 3 Nearshore Fixed Oscillating

See Type 4 Nearshore heaving

See Type 3 Nearshore Fixed Oscillating Position keeping mechanism

See Type 3 Nearshore Fixed Oscillating Position keeping mechanism
APPENDIX F  TYPE 6

Type 6  Offshore Large Body

- Foundation
- Position keeping system
- See Type 1 Offshore-Heaving

RS

- Support structure (floating platform)
- Flooded cavities
- Watertight cavities
- Ballast
- Structure
- Geometry adjustment mechanism
- See Type 1 Offshore-Heaving Support structure

HS

- Extracting mechanism
- Oscillating water column
- Water channel
- Air chamber
- Diaphragm

- See Type 1 Nearshore fixed oscillating Active alignment mechanism
- See focusing mechanism

- Drive
- Power
- Arms
- Water reservoir
- Attachment to PTO

- Overtopping
- Overlapping mechanism
- Geometry adjusting mechanism
- Structure

- Air chamber
- Diaphragm
- Attachment to PTO
- Diaphragm attachment
APPENDIX G   TYPE 7

[Diagram showing Type 7 Nearshore Fixed Large Body with subcategories RS and HS, and references to Type 3 and Type 6]

APPENDIX H   TYPE 8

[Diagram showing Type 8 Shoreline Large Body with subcategories RS, HS, Support structure, and Foundations, and references to Type 3 and Type 6]
APPENDIX J  WAVESTAR HS & RS COMPONENTS