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Integration of energy converters in multi-use offshore platforms

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Table of contents

List of figures

List of tables

Executive summary

The present document aims at analyzing the main aspects concerning the integration of energy converters in multi-use platforms, which represent an evolution of the well-known commercial offshore farms characterized by wind or current energy. Multipurpose platforms represent a topic of increasing interest since they promote a better usage of the renewable resources contemporary available in an offshore area, reduce the electrical and civil infrastructures, as well as, construction and O&M costs and environmental impact.

After a brief description of the State-of-the-art of multipurpose platforms designed to the present, a methodology for integrating energy converter in offshore platform is presented. In addition to the methodology, numerical models were developed to further support the comprehension of the main issues relevant to the realization of multiuse platforms both connected to the grid and/or stand-alone.

Finally, case study applications are described.

1 Introduction

During recent years, energy demand has increased significantly throughout the world. For this reason, new renewable energies have been created and their development has been increased during years.

In the area of renewable energy, marine renewable energies have undergone significant development during the past 20 years. Different devices have been developed, tested and used to extract energy from wind, waves and currents. All of these devices have been built to extract energy from only one resource available in each location.

Review of the State-of-the-art of all the devices developed to the present in order to extract energy from the waves, wind and currents can be found within the tasks 3.2 and 3.3 of the present work package.

Currently, there are commercial offshore farms in the sea with wind turbines and turbines to extract energy from currents (tidal devices) and experimental devices or farms to extract energy from the waves. In fact, all these offshore farms only allow us to extract energy from one of the three resources available in the ocean.

However, during recent times new concepts of multipurpose platforms are being designed to extract energy from waves, wind and currents in the same place. The main goal of the multipurpose platform development is to achieve:

- An increase in the amount of usable resources in each area

- Reduce the cost of offshore renewable energies (use of electricity grids and cost reduction in operation and maintenance issues).
- Reduce the environmental impact.

Currently, two different multipurpose platforms concepts are been designed and developed:

1. Sharing structure concept- the same platform is formed by different converters of wave, tidal or wind turbine energy.

2. Sharing space concept - in the same area different devices of wind, wave and tidal are placed with the main goal of taking advantage of the available space in the offshore farms

The following section is a brief description of the State-of-the-art multipurpose platforms designed to the present.

1.1 Review of the state of art of multi-use platforms

During last years, different European projects and private companies have developed many multi-use offshore platforms. The multi-use platforms have main target of extract energy from wave, wind and currents combined different uses in the same space.

In this section, a brief description of the most promising multi-use platform designed to the present will be done.

Moreover, multi-use offshore platform designed in the following European project will be exposed:

- Marina Platform
- Tropos Project
- H2Ocean

1.1.1 Poseidon Wave/Wind Energy Platform [1]

Table 1 and Figure 1 shows the main information about Poseidon Platform.

Name	Company	Offhsore Technology	Combined Uses	Link
Poseidon	Poseidon Floating Power	Floating Foundation	Wind-Wave	http://www.floatingpowerplant.com/

Table 1. Main characteristic of Poseidon platform.

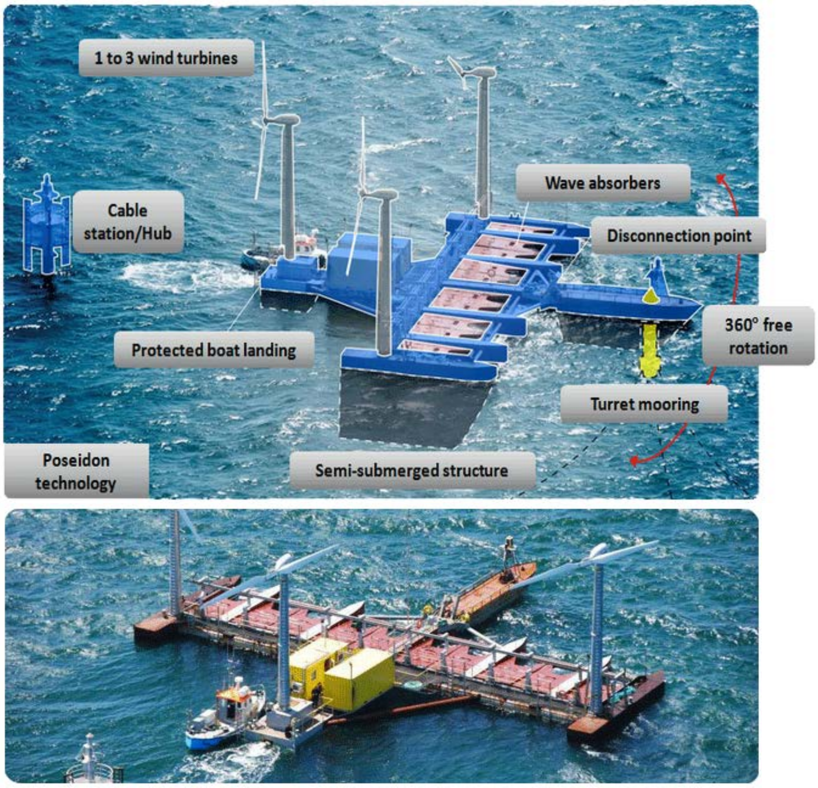


Figure 1. Poseidon Platform [1]. [1]

1.1.2 2Wave1Wind [2]

Table 2 shows the main information about 2Wave1Wind Platform.

Name	Company	Offhsore Technology	Combined Uses	Link
2Wave1Wind	Ocean Wave and wind Energy	Fixed Foundation	Wind-Wave (wave dragon and point absrober)	http://www.owwe.net/

Table 2. Main characteristic of 2Wave1Wind platform.

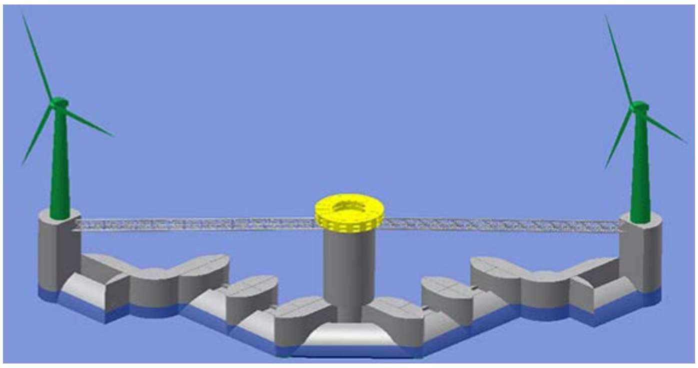


Figure 2. 2Wave1Wind Platform [2].

1.1.3 W2Power (floating Wind-Wave combinations) [3]

Table 3 and Figure 3 shows the main information about W2Power platform.

Name	Company	Offhsore Technology	Combined Uses	Link
W2Power	Pelagic Power	Semi-Submersible floating platform	2Wind Turbines-Wave (point absrober)	http://www.pelagicpower.no/

Table 3. Main characteristic of W2Power platform.

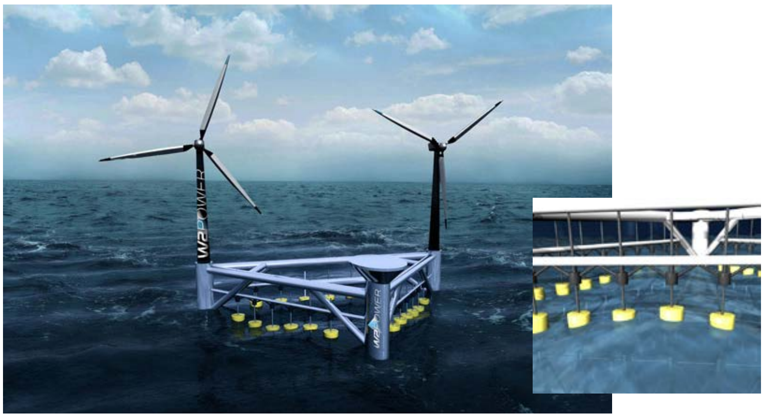


Figure 3. W2Power platform [3].

1.1.4 Wavetreader (wind + wave) [4]

Table 4 and Figure 4 shows the main information about Wavetreader Platform.

Name	Company	Offhsore Technology	Combined Uses	Link
Wave Treader	Green Ocean Energy	Fixed pile/monopile	Wind - Wave	http://www.power-technology.com/

Table 4. Main characteristic of Wavetreader platform.

Figure 4. Wavetreader platform [4].

1.1.5 Seagen W (wind + tidal [11])

Table 5 and Figure 5 shows the main information about Seagen W.

Name	Company	Offhsore Technology	Combined Uses	Link
Seagen W	Seagen	Fixed pile/monopile	Wind - Tidal	http://www.marineturbines.com/

Table 5. Main characteristic of Seagen W platform.

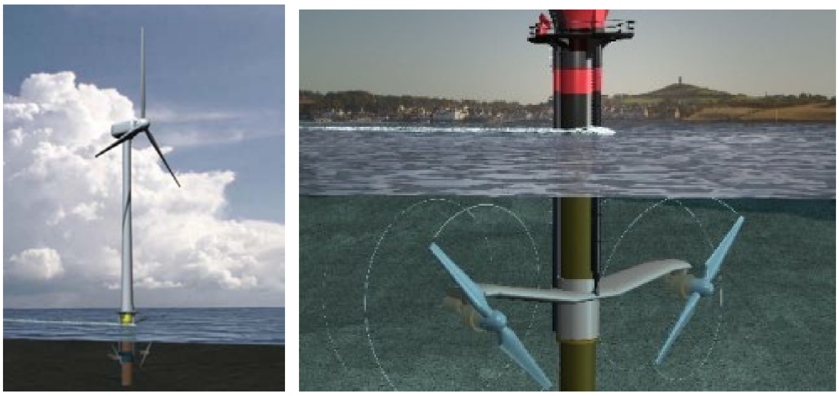


Figure 5. Seagen W platform [11].

1.1.6 WEGA: Hybrid Coupling (Wind turbine + WEC [6])

Table 6 and Figure 6 shows the main information about WEGA Platform.

Name	Company	Offhsore Technology	Combined Uses	Link
WEGA	Sea For Life, Lda	Fixed pile/monopile	Wind - Wave - Other uses	http://www.seaforlife.com/

Table 6. Main characteristic of WEGA (Hybrid Coupling) platform.

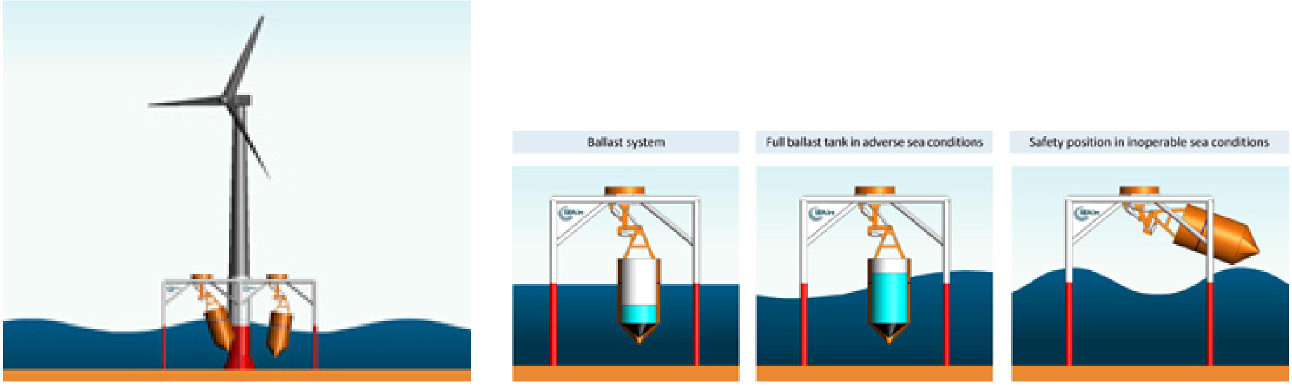


Figure 6. WEGA (Hybrid coupling) platform [6].

1.1.7 Multi-use developed during Marina Platform Project [7]

During Marina Platform Project three multi-use platform were designed and tested in different laboratories around Europe.

The main characteristics of these platforms will be summarized in the following sections.

1.1.7.1 Large floating platforms with multiple WECs (Marina Platforms: Semisubmersible platform + OWC)

Table 7 and Figure 7 shows the main information about Marina Platform: Semi-Submersible Platform with oscillating water columns and wind turbines.

Name	Company	Offhsore Technology	Combined Uses	Link
-	Marina Platform, European Project	Semi-Submersible floating plataform	Wind - Wave (OWC)	http://www.marina-platform.info/

Table 7. Main characteristic of Marina platform: Large semi-submersible - Wind Turbine + multiple OWC.

Figure 7. Marina platform: Large semi-submersible - Wind Turbine + multiple OWC [7].

1.1.7.2 *Floating semi-submersible with 3 WECs (Marina Platform: Innovative combination of exiting concepts Braceless semi-submersible and rotating WECs)*

Table 8 and Figure 8 shows the main information about Marina Platform: Semi-Submersible Platform with 3 WECs and wind turbines.

Name	Company	Offhsore Technology	Combined Uses	Link
-	Marina Platform, European Project	Semi-Submersible floating plataform	Wind - Wave (Flaps)	http://www.marina-platform.info/

Table 8. Main characteristic of Marina platform: Floating semi-submersible with 3 WECs.

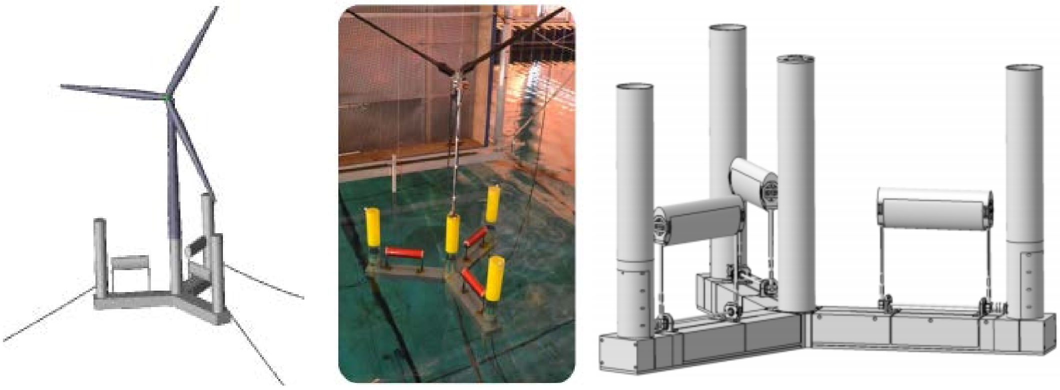


Figure 8. Marina Platform: Floating semi-submersible with 3 WECs [7].

1.1.7.3 *Floating wind turbine with 1 WEC (Marina Platform: Combination of SPAR and Torus)*

Table 9 and Figure 9 shows the main information about Marina Platform: Semi-Submersible Platform with 1 WEC – SPAR + TORUS.

Name	Company	Offhsore Technology	Combined Uses	Link
Torus	Marina Platform, European Project	SPAR Floating Buoy	Wind - Wave (Point Absorber)	http://www.marina-platform.info/

Table 9. Main characteristic of Marina platform: Floating turbine with 1 WEC.

Figure 9. Marina platform: Floating turbine with 1 wec [7].

1.1.8 Multi-purpose platform design in TROPOS Project [8]

During Tropos Project two multi-use platform were designed and tested in different laboratories around Europe.

The main characteristics of these platforms will be summarized in the following sections.

1.1.8.1 Leisure Island Concept-Canary Island

Table 10 and Figure 10 shows the main information about Tropos Platform: Leisure island concept – Canary Island.

Name	Company	Offhsore Technology	Combined Uses	Link
Leisure Island Concept	Tropos, European Project	Floating Platform - Island Concept	Multi use-Energy productions and leisure	http://www.troposplatform.eu/

Table 10. Main characteristics: Tropos Platform: Leisure island concept – Canary Island.

Figure 10. Tropos Platform: Leisure island concept – Canary Island [8].

1.1.8.2 Green and Blue Concept – Creta

Table 11 and Figure 11 shows the main information about Tropos Platform: Green and Blue concept – Creta.

Name	Company	Offhsore Technology	Combined Uses	Link
Green and Blue Concept	Tropos, European Project	Semi-Submersible floating plataform	Wind - Aquaculture	http://www.troposplatform.eu/

Table 11. Main characteristics: Tropos Platform: Green and Blue concept – Creta.

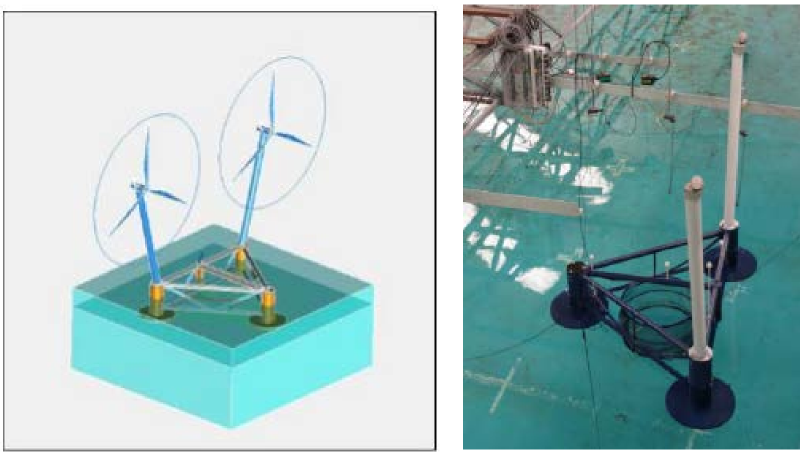


Figure 11. Tropos Platform: Green and Blue concept – Creta [8].

1.1.9 Offshore Power Farm [9]

Table 12 and Figure 12 shows the main information about offshore power farm.

Name	Company	Offhsore Technology	Combined Uses	Link
Offshore Power Farm	Offshore Island Ltd.	Fixed plataform	Wind - Wave -Current	http://www.offshoreislandslimited.com/

Table 12. Main Characteristics of Offshore Power farms.

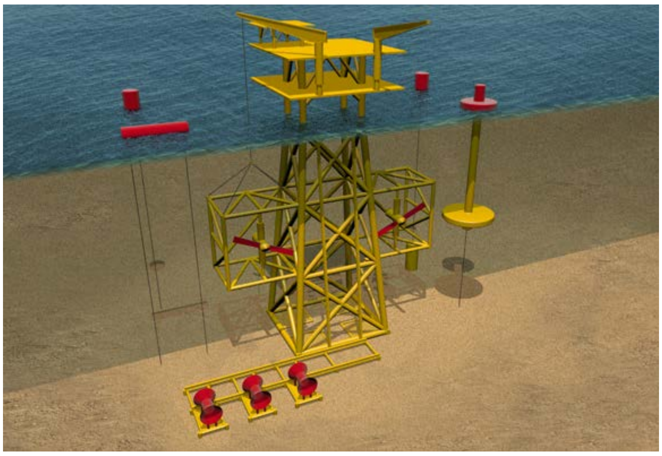


Figure 12. Offshore Power farm.

1.1.10 HEXICON: floating platform for multiple purpose [10].

Table 13 and Figure 13 shows the main information about offshore power farm.

Name	Company	Offhsore Technology	Combined Uses	Link
H3W-18MW	Hexicon	Floating plataform	Wind - 18 MW	http://www.hexicon.eu/
H3-18MW			Wind - 18 MW	http://www.hexicon.eu/
H4W-24MW			Wind - 24 MW	http://www.hexicon.eu/

Table 13. Main Characteristics of Hexicon Platforms.

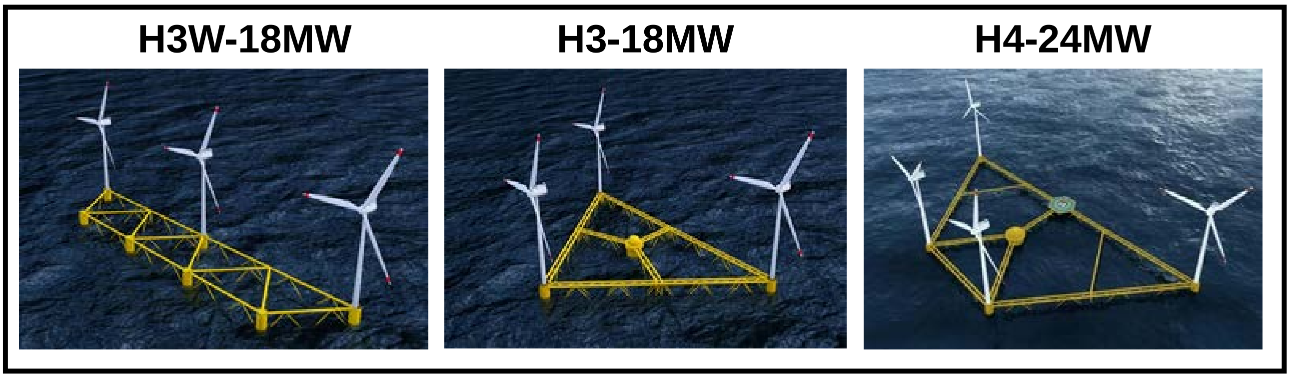


Figure 13. Hexicon platform [10].

2 Methodology to integrate energy converters in offshore platforms

During this section, a new methodology has been developed to incorporate different types of energy converters inside offshore platforms (multi-use platforms – integration in single platforms) or inside offshore farms (integration in multiple single devices). The new methodology will aspire to explain how the process to incorporate different energy converters inside offshore farms is.

The methodology proposed to integrate energy converters is divided in 5 different stages. They have to be followed one after each other. Always the next step requires the inputs obtained from the previous ones.

The different steps of the methodology proposed are:

1. Analysis of climate conditions at selected site.
2. Power Take Off (PTO)
3. Selection.
4. Offshore Technology.
5. Technology Integration and Farm design.
6. Environmental Impact Assessment (EIA).
7. Other possible uses to incorporate in the offshore farms,

Next figure (Figure 14) appears a brief description of the methodology proposed.

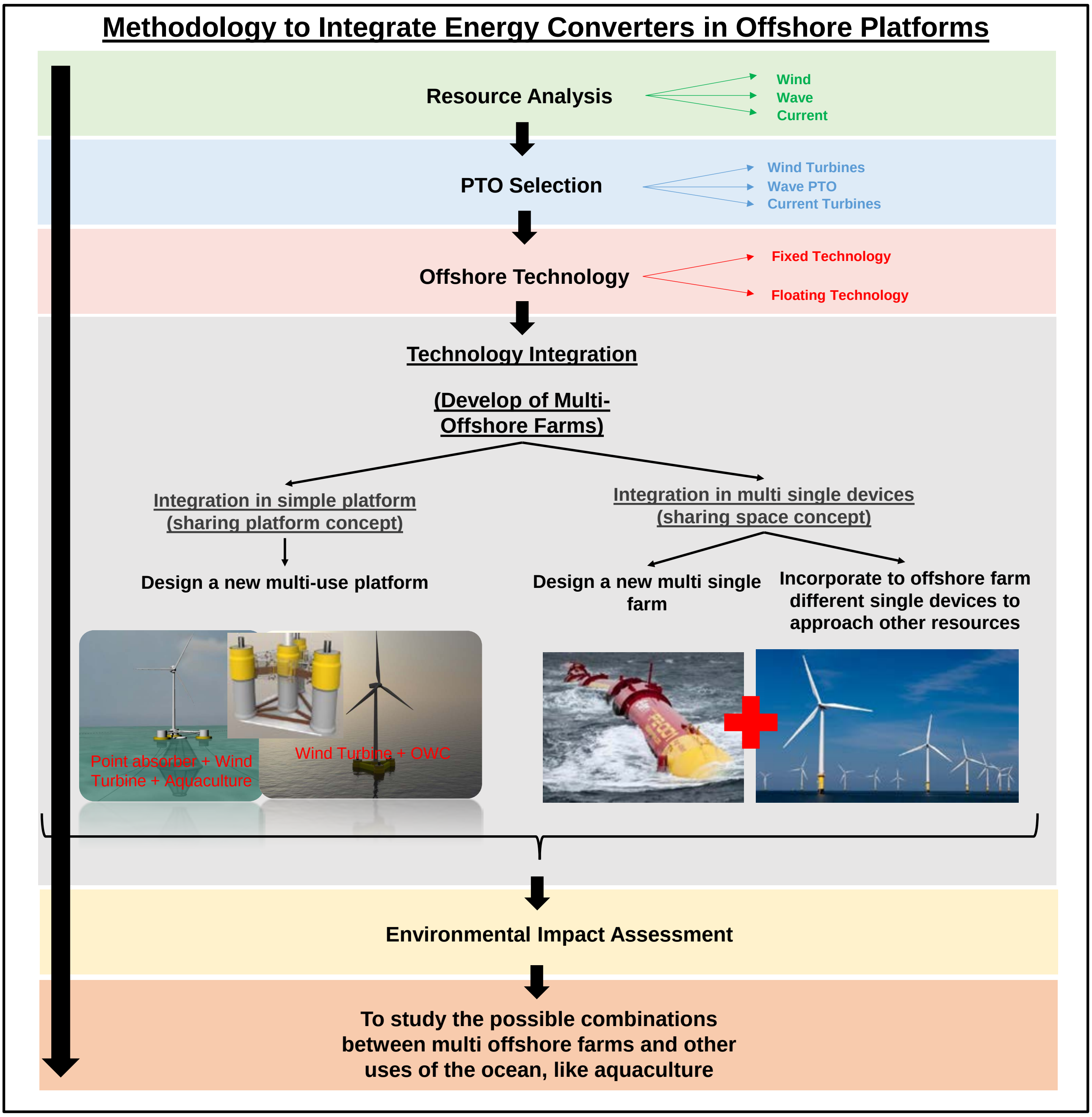


Figure 14. Methodology to integrate energy converters in offshore platforms.

To develop the new methodology to integrate energy converters inside offshore platforms we have taken into account all background generated during the previous task developed in the work packaged 3 of Mermaid project (3.1 Assessment of ocean renewable energy resources, 3.2 Offshore Technology and 3.3 Energy Converters).

During next points of this document, a brief description of each phase of the methodology will be exposed.

2.1 Analysis of Climate conditions at selected site

In order to maximize the production of offshore farms, the goal of the first phase is to identify the resource available at selected site. The determination of the resource in site selected can be considered as one of the most important phase of the energy converters integration stages.

The resource analysis (wind intensity/velocity, wave energy and current velocity) will be done through instrumental buoys available at the selected site and by means of reanalysis data base (like GOW for waves).

The analysis of the different resources available in the ocean, wind, wave and current, can be found in the ***Work Task 3.1 Assessment of ocean renewable energy resource*** of the present project. Moreover, the resource available in the fourth Mermaid site are available in the ***"Work task 3.1.1 Assessment of offshore wind energy resources, 3.1.2 Assessment of wave energy resources and 3.1.3 Assessment of marine current energy resources"***, as well as in Work package 7 will appears the specific met-ocean conditions for the four selected sites at Mermaid Project (North Sea, Baltic Sea, Atlantic Ocean and Mediterranean Sea).

As a general and first approach, the Table 14 shows the minimum resource required to incorporate specific devices (wind/wave/tidal) inside multi offshore farms.

In the first stage wind, wave and current conditions will be analyzed as individual resources.

Resource Analysis

Resource Analyzed	Minimum value required to include the resource studied in the multi purpose offshore Farm
Wave	Wave Energy Resource > 15Kw/m
Wind	Wind Energy Resource >7m/s
Currents	Current Energy Resource >1m/s

Table 14. Resource Analysis: Selection Criteria.

Based on Table 14, the resource to be harvested will be selected.

2.2 PTO Selection

Once the prevailing resource of energy has been identified and once the feasibility of harvesting one or other sources of energy is ensured, the next objective will be to select the most suitable PTO for each source of energy considered.

It has to be highlighted that the underlying objective is to maximize power production.

Next, as an example, a list of PTO for each energy resource is given. A comprehensive description of the PTO for wave, wind and current can be found in the ***"Work Task 3.3 Energy Convertors".***

2.2.1 PTO for Wave Energy

A brief enumeration of PTO for wave energy exiting, currently, is here presented. The review of the state of art of wave energy device can be found in the ***"Task 3.3.2 Wave energy Converters"*** of the present project.

- Air Turbines – Oscillating water columns
    - Well Turbines, Dennis Auld, Impulse Turbines, Radial Turbines, Cross flow and Savonious Turbines.
- Hydraulic Turbines: Sendekia
- Hydraulic Circuits and systems: Oyster, Pelamis, Wedg, others.
- Direct-drive generators: Wavestar, Wedge, Penguin-Wello,

Likely, the WEC and PTO selected for each location will be in function of the wave intensity and water deep.

2.2.2 PTO for Wind

A brief enumeration of the PTO for offshore wind converters exiting currently is here presented. The review of the state of art of wave energy device can be found in the ***"Task 3.3.1. Offshore wind energy converters"*** of the present project.

- Horizontal Axis Turbines.
- Vertical Axis Turbines: Vertiwind project, Nenuphar.
- Other Technologies: H-rotor, Darrieus turbine, Savonius Rotor.

Presently, horizontal axis wind turbine are commonly used in onshore and offshore wind farms.

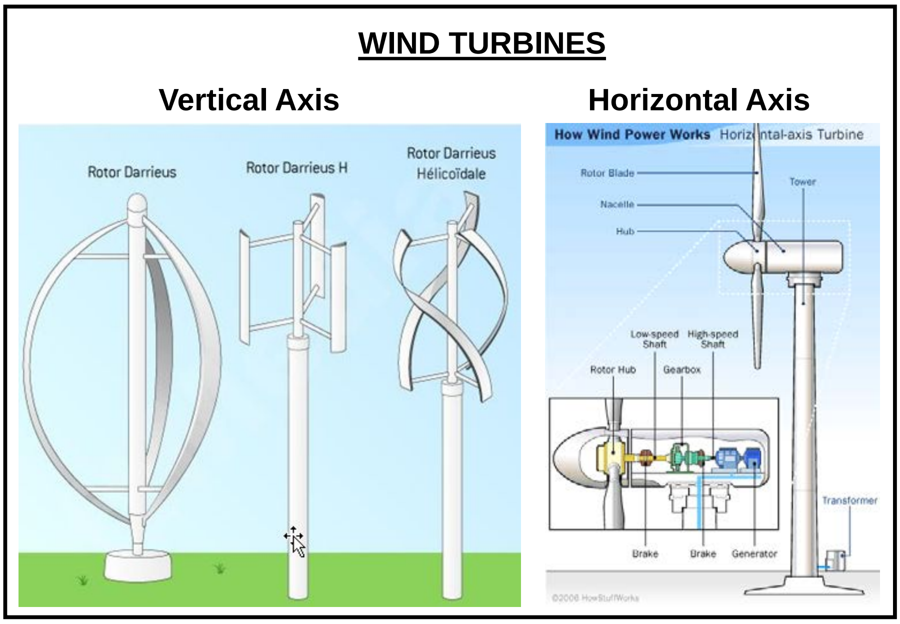


Figure 15. Main PTO for wind ([12]).

2.2.3 PTO for Currents

A brief enumeration of current energy converters exiting currently is here presented. The review of the state of art of wave energy device can be found in the ***"Task 3.3.3 Offshore current energy converters"*** of the present project.

- Horizontal Axis Turbines.
- Vertical Axis Turbines.
- Reciprocating hydrofilis.
- Tidal Kite.
- Venturi Tube.

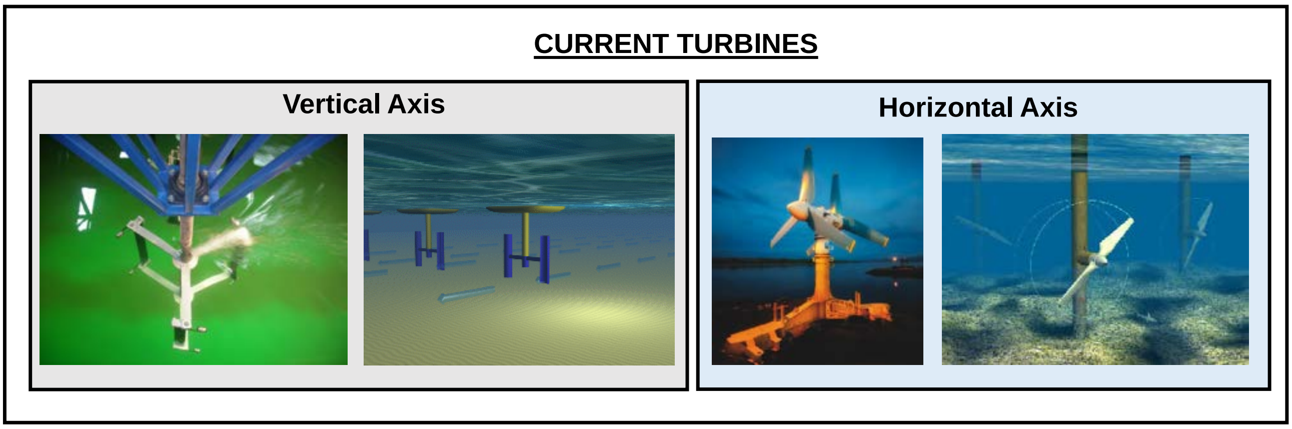


Figure 16. Main PTO for Current: Vertical Axis: Left [13], Rigth [14]. Horizontal Axis: Left [15], Rigth [16].

2.3 Offshore Technology

Once the prevailing resource has been identified and selected the most suitable PTO, the most adequate offshore technology have to be selected, both in terms of offshore structures and grid connection technologies: a comprehensive description of both of them is given in deliverable 3.4.1 of Work Task 3.4 "Integration of energy converters in multi-use offshore platforms.

There are two main groups of offshore structures divided in function of the water depth:

- Fixed Structures: Shallow Water - h<50 meters.
- Floating platforms: Deep water - h>50 meters.

They can be selected based on water depth.
A brief list of different fixed and floating structures typology is shown next.

2.3.1 Fixed Structures

The current fixed structures technologies can be summarized on the following alternatives:

- Monopile (h<30 m).
- Gravity Base foundation (h<30 m).
- Suction Bucket (h<50 m).
- Tripod (h<30 m).
- Tripile (h>50 m).
- Jacket (h<50 m).

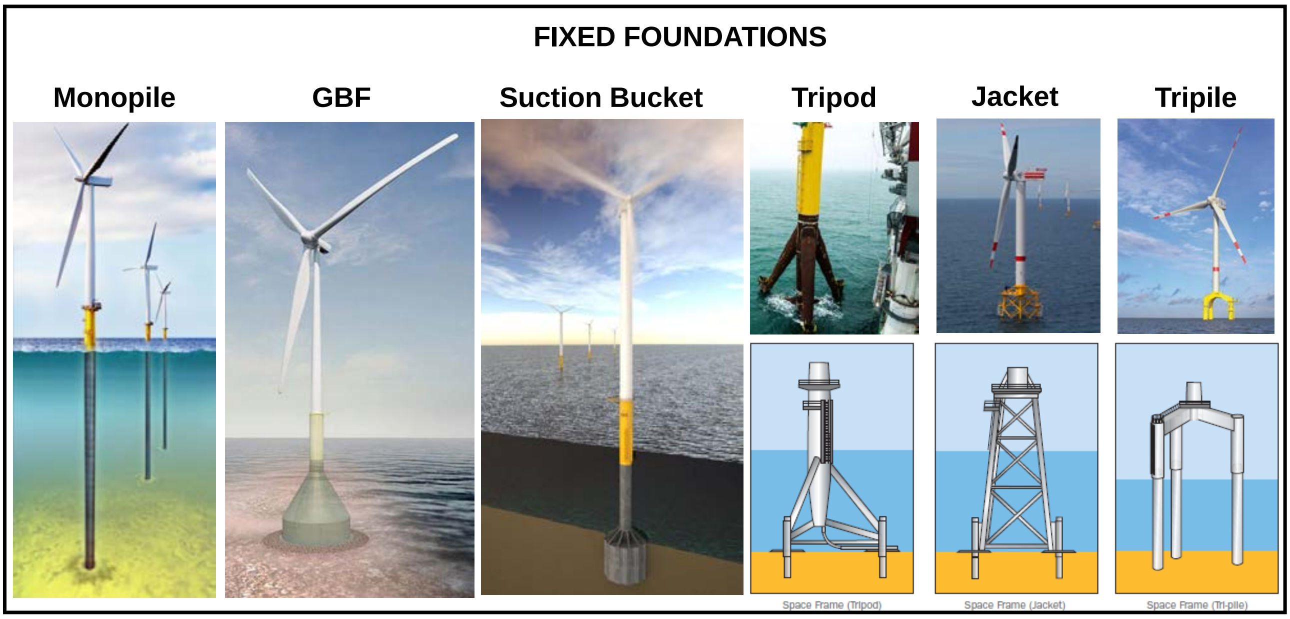


Figure 17. Offshore Technology: Fixed Foundation.

In the case of a fixed structure being selected, its typology should be defined according to water depth and geotechnical constraints.

2.3.2 Floating Platforms

There are four floating platforms technologies:

- Barge (h>30 m).
- SPAR buoys (h>100 m).
- TLP buoy (h>100m).
- Semisubmersible Platform (h>50 m).

FLOATING FOUNDATIONS

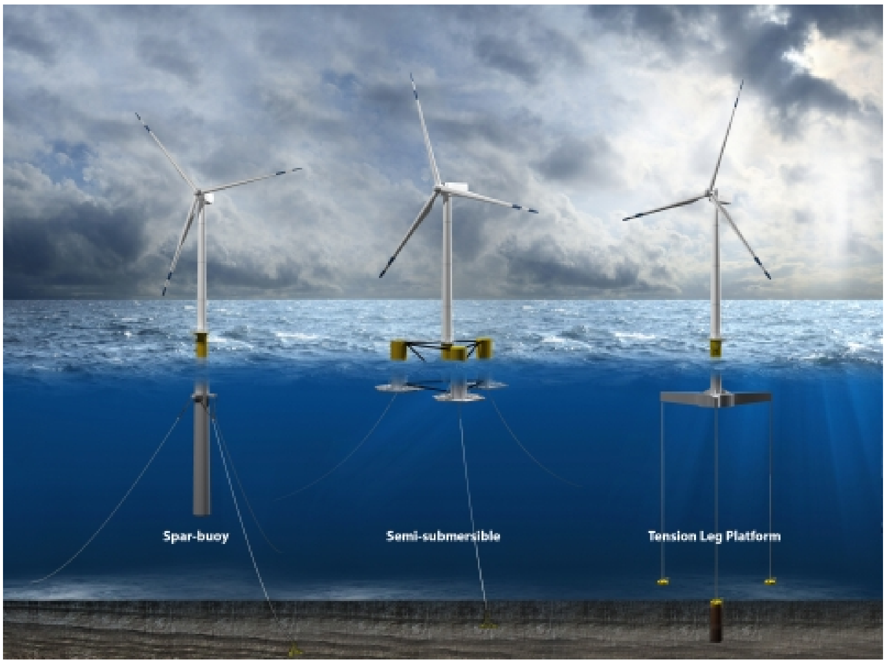


Figure 18. Offshore Technology. Floating Foundations [17].

The most suitable typology should be selected according to water depth. The mooring system as well as the anchoring system must be chosen based on sea bed characteristics, geotechnical constraints and water depth.

2.4 Technology Integration

Once the resource has been analyzed and PTO and offshore technology have been selected, the next step of the methodology proposal consists of incorporating different energy converters in the same site or in the same platform.

The goal of the present point is to establish how different energy converters, wind, wave and tidal, have to be integrated in the same area in order to maximize energy production.

Nowadays, wind energy farms (commercial phase) are already in commercial phase around Europe (presently all wind offshore farms are in the North and Baltic Seas). On the other hand, wave energy and current devices (experimental phase) are in first design phases with medium or full scale prototypes, all of them placed in different test sites.

Therefore, as a first approach, and taken into account the considerations taken in the previous paragraph, nowadays, the most profitable renewable marine resource is wind, so the future multi-use offshore farms should be formed by wind turbines (as a main energy converter) and as complement according to the characteristics of the area studied. Different tidal/wave converters could be coupled to the offshore farm in order to maximize offshore energy production.

Currently, almost every places around Europe's shore where wind conditions are optimal to generate energy, also have enough wave resource to share the same offshore area and maximize offshore energy production and reduce energy cost. On the other hand, current resources are located in very specific places, manly bays or estuaries, where wind and waves conditions are not related with the currents. So firstly, the integration of different technologies in the same area should be formed by wave and wind energy converters while current devices will only be included in specific offshore sites.

The process to share the same ocean space is presently in the first stage, so as a first approach, one solution could be to include wave or tidal (only in specific areas) devices between wind energy turbines located inside commercial offshore wind farms (different devices located in the same area). This concept will be called ***"sharing space"*** from now on.

In the second stage of the process, for future "energy farms" and taken into account that the main goal is to maximize energy production, specific platforms formed by different energy converters will be designed. The new multi-use platform will share the space and platforms (offshore technology). This new concept called ***"sharing structure"*** from now on, will allow for increasing the performance of future energy offshore farms.

Summarize the information shown in the previous paragraph, two different types of multi-purposes farms will be developed during the coming years:

- For present farms: Sharing space (For wind farms operating currently or even for future farms taken into account in the design of the lay out, the incorporation of different wave/current devices between wind turbines).
  Several individual devices (wave energy converters, wind energy turbines and current turbines) will be used in the same area, sharing space and logistics.

- For future farms: Sharing structure (For future park design).
  The same structure or platform (fixed or floating) will be sharing uses or energy harvesting technologies (wind, waves or current).

Technology integration decision should be made considering the compatibility between uses, identified synergies between uses among others.

2.4.1 Sharing space.

As was commented in the introduction of this section, the main idea proposed in this point aspires to incorporate other devices inside the wind farms already built. Moreover, the wave resource available in the places with OWF (offshore wind farms, see Figure 19) is normally suitable to incorporate wave energy devices.

Figure 19. Offshore Wind Farm (OWF) [18].

Currently, many offshore farms are in operation and almost all of them are located in the North and Baltic Seas (shallow water, offshore technology – fixed structures); however, the capacity of the grid connection is generally not used at 100 % of the total capacity. The WECs incorporated in the OWF will be linked to the grid connection using the extra capacity available in the cables of the OWF. In addition, if the current resource is suitable in the studied area, current converters also could be incorporated to the multi-use farm.

On the other hand, the combination of wind, wave and current energy devices in the same area should satisfy some layout requirements in order to maximize energy production and reduce destructive interaction between energy devices. The minimum distance between each device depends on the technical characteristics of the devices used.

- In the case of wave energy converters, the minimum distance between devices is given by the radiated energy of the converter (this distance change for each kind of WEC).

- In the case of wind turbines the minimum distance between turbines is in function of the wake generated (5*Diameter of the blades) downstream.

As a general approach, the wave energy converters could be installed just ahead the wind turbines with the goal of reducing the wave loads around the wind turbine support. This approximation could only be used in those situations where the layouts of the wave energy converters were optimal in order to maximize the wave energy production.

The next table (Table 15) gives a first approach to the recommended distance between devices.

Devices	Wave	Wind	Current
Minimum Distance Between Devices	~200 m	~700 m	~200 m

Table 15. Recommended distance between devices.

Figure 20. Multi-purpose offshore farm: Sharing space concept: Wind Turbines + Wave Star [19].

The incorporation of other energy converters (mainly wave energy converters or even tidal turbines) inside OWF will enable us to obtain many advantages displayed in the next list:

- Sharing tools and data for environmental impact studies.
- Sharing the grid connection with the reduction of offshore installation.
- To reduce ocean uses.
- To reduce environmental impact.
- To maximize energy production in the OWF.
- To reduce wave loads, installing wind or tidal devices in front of the wind turbines.
- To reduce the offshore energy cost.
- Sharing logistics and infrastructures present in the area.

2.4.2 Sharing structure.

A sharing structure consists of designing a new “Multi-Use Platform”. The new platform will be formed by different energy converters located in the same structure. In section 1 of the present document a brief state of art of multi-use platform has been shown.

These new platforms will be designed for the future offshore farms with the main goal of achieving all advantages shown in the previous points and to reduce the number of foundations/anchors in the offshore farms. Therefore, it is likely that the environmental impact (EI) generated by multi-use platforms in the sea bed could be lower than the EI caused for multi-devices farms due to the reduction in the number of foundations and anchors over the sea floor.

The multi-use platforms will be designed taking into account the resource available, the water depth and geological constraints. The new multi-use platform design should combine all uses available in the selected location.

The layout of this kind of "Multi-Use Platforms" will be defined by the prevailing conversion technology (as was describe below Wind energy) and the recommended minimum distance between energy converters.

In the case of creating a new farm with wave, wind and current devices the minimum distance between MUPs will be given by the wind turbines minimum distance (see Table 15).

Figure 21 shows different sharing structures, where different uses like wind energy turbines, wave energy converters or even aquaculture cages share the same ocean space.

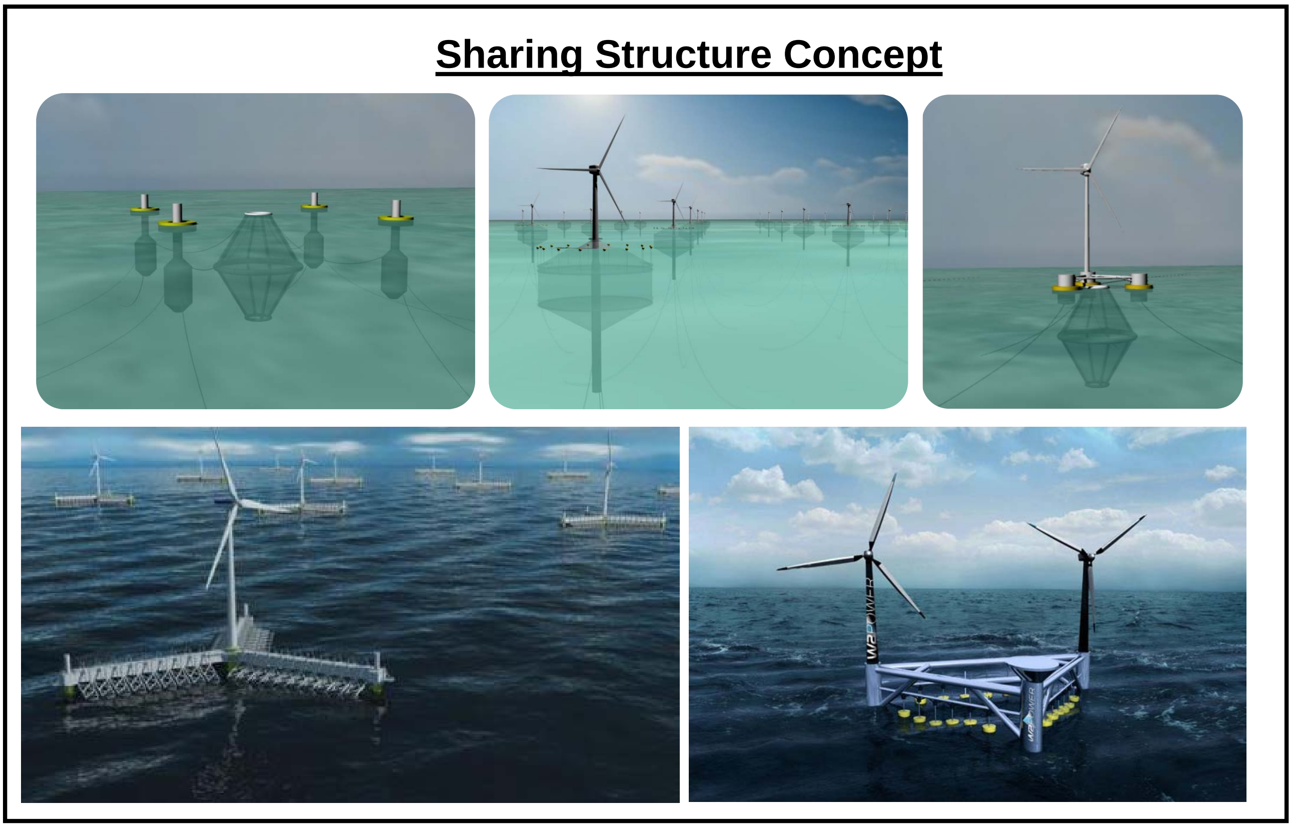


Figure 21. Multi-purpose offshore farms: Sharing structure concept: (wind + wave + aquaculture): Wave star + wind turbine [19], W2Power platform [3].

2.4.3 Other ocean share uses

The future multi offshore energy farm could also share the ocean space with other uses. The following list suggest different combined uses within the different ocean areas (shore line, shallow water or deep water):

1. Energy converters (wind and/or wave and/or tidal) with aquaculture uses – Shore line – Shallow water – Deep water.

2. Energy converters (wind and wave converters) with breakwaters – Shore Line.

Figure 22. Different combined uses: Break water + OWC or Wind Turbines: [20].

2.5 Environmental Impact Assessment

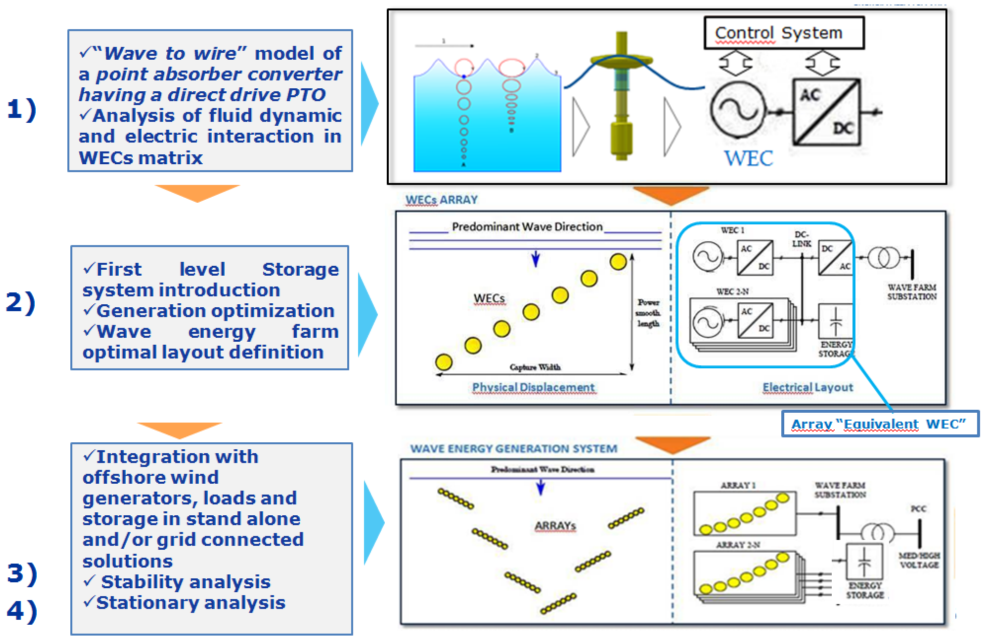
The environmental impact study will be formed by the analysis of positive and negative impacts generated with the deployment of a multi uses platform farm as well as with the study of mitigations options.

Moreover, other aspects like the influence of climate challenge, irreversible environmental effects and non-linear effect are also recommended.

Because of this, a new methodology to assess environmental impact generated for the future multi-use offshore farms will be developed inside Mermaid project (Work Task 3.5 Conceptual impact assessment for multi-use offshore platforms).

3 A numerical model for the integration of WEC in MUP

In this chapter details of numerical models for the integration of Wave Energy Converters (WEC) in Multi-Use Platforms (MUP) are given.
A step by step modeling approach, consisting of 4 analysis stages, was followed.



1)
✓"***Wave to wire*" model of a point absorber converter having a direct drive PTO**
✓Analysis of fluid dynamic and electric interaction in WECs matrix

2)
✓First level Storage system introduction
✓Generation optimization
✓Wave energy farm optimal layout definition

3)
4)
✓Integration with offshore wind generators, loads and storage in stand alone and/or grid connected solutions
✓ Stability analysis
✓Stationary analysis

Figure 23. Adopted numerical modeling approach.

The first modeling stage aims at providing a "wave to wire" model of an array of Wave Energy Converters of Point Absorber type. The converters are interconnected on a common electrical Direct Current (DC) that sum the DC single power outputs coming from each WEC: in this way the array can be seen by the electrical grid as a single power producer characterized by a DC power profile more regular and less oscillating than the one of a single WEC.
Starting from the equation of motion of each converter and taking into account the associated hydraulic and hydrodynamic aspects the DC power output of such an array is modeled, considering, for each WEC of the array, the presence of an electrical drive based on reactive control technique. According to this technique, the electrical linear machine can operate as generator as well as motor in order to maximize the power extraction from the waves. With this modeling stage, it is possible to study the interactions between several WECs and understand the effect on the DC global generated power profile of both their mutual position and the presence of other submerged structures (e.g. Wind Turbine Generator foundation).

The purpose of the second modeling stage is to study generation optimization aspects, in order to create a sort of an equivalent WEC of an array of wave energy converters model, hereafter "array-equivalent WEC", able to provide an Alternating Current (AC) continuous, stable and grid compliant generation in the range of some tens-hundreds of kW: in this phase principal modeled issues were DC generation collection, first level storage system introduction, sizing of storage and inverter components and definition of their control strategies.

The two last modeling steps are both relevant to the integration of “array-equivalent WEC” models with offshore wind generators, loads like the one of fisheries and storage devices to simulate the stationary and dynamical behavior of both grid connected and stand-alone offshore multiuse platforms. In particular the third stage is aimed at investigating stability aspects (frequency and voltage regulation) on short periods of analysis (in the order of some seconds) while the fourth one has the purpose of allowing a long period energetic analysis (of tens of years) taking as input hourly (three-hourly or even daily) resources time series. This approach allows the correct sizing and control rules identification of storage systems and/or other regulation components.

As a consequence the chapter is organized in two sections:

- the first section is related to the modeling of the hydrodynamics around the WECs: the output of this modeling phase constitute the input for the electrical modeling of an array of point-absorber type WEC, operating in different configurations, as part of stage 1 analysis;
- the second one describes all the modeling choices made to simulate the electrical aspects of interest in all the four stages of the adopted modeling approach.

In the next paragraphs it will be presented how the models work and their applications to significant case studies. According to the modeling approach previously described chapter 3 is organized in two main sections, the first dedicated to the description of the modeling and simulation results of hydraulic aspects and the other relevant to modeling and simulation results of electrical aspects.

3.1 Hydraulic model (Modeling stage 1)

The wave field in open sea with the presence of one wave energy converter is composed by incident waves, diffracted waves and waves radiated by the Wave Energy Convertors (WEC) motion. To model the complexity of the wave field around the WEC, together with the WEC motion, a three dimensional (3D) model is needed. When more wave energy converters are located close to each other, the wave field around one device is obviously influenced by the wave field produced and modified by the other devices, and therefore the complexity of the modified wave field increases. When many converters work as a battery, they are located over a large sea area, and there is the need to perform several simulations in order to optimize the WECs layout to maximize the wave energy production.

In this section a detailed description of the numerical model built to simulate the wave field in sea area with the presence of wave energy devices is given. In particular it has been implemented a 3D model which very accurately reproduce the wave field interacting with the WEC motion. The model, described in the next section 3.1.1 is able to simulate various WEC with different geometry and laws of motion. The only assumption is that of small amplitude wave and small amplitude WEC motion. This model has been used coupled with the electric model, which solves the electrical part of the WEC system (model described in section 3.2).

In a dedicated section (3.1.2) is presented a numerical model, which allows reproducing large sea areas with a battery of WECs in a 2D domain, reducing therefore the computational costs without decreasing the results accuracy.

3.1.1 Three-dimensional numerical model of hydrodynamics around a WEC

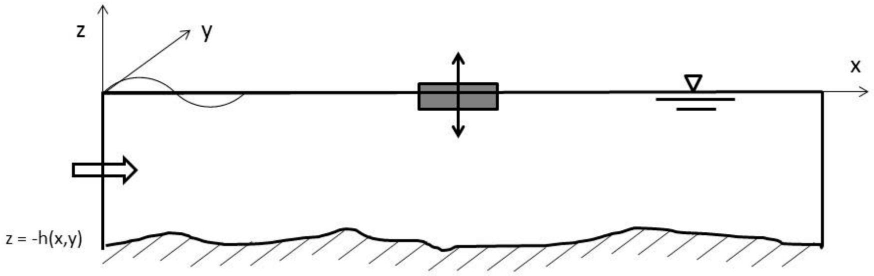


Figure 24: sketch of a vertical section of the model domain

In the assumption of small amplitude wave and small amplitude WEC motion, the mathematical problem that expresses the wave field interacting with a point-absorber wave energy converter, can be formulated by linearized equations. In Figure 24 is sketched a sea area with the presence of one point absorber wave energy device. Given the system of reference represented in the figure, the wave equation in the frequency domain are:

$$\begin{aligned}
&\nabla^2\Phi = 0 && \\
&\Phi_z = \omega^2/g\Phi; && z = 0 \\
&\Phi_z + \nabla_h h \cdot \nabla_h \Phi = 0; && z = -h(x,y) \\
&\Phi_x + ik\Phi = \frac{2a'g}{\omega}k\frac{\cosh(k(h+z))}{\cosh(kh)}; && x = 0 \\
&\Phi_x + ik\Phi = 0; && x = x_{end} \\
&\Phi_n = Z && \text{at the WEC boundaries(}
\end{aligned} \tag{3-1}$$

Where $\Phi(x,y,z,\omega)$ is the fluid velocity potential, ω is the angular frequency, g is the gravitational acceleration, $h(x,y)$ is the water depth, k the wave number, a' the incident wave amplitude and $Z(\omega)$ is the complex WEC velocity.

The WEC motion is imposed to have the following time series of displacement, velocity and acceleration:

$$\begin{gathered}
z(t) = \frac{iZ}{\omega}e^{-i\omega t} \\
\dot{z}(t) = Ze^{-i\omega t} \\
\ddot{z}(t) = i\omega Ze^{-i\omega t}
\end{gathered} \tag{3-2}$$

Solution of problem **(3-1**) can be obtained solving simultaneously the ordinary differential equation that governs the WEC motion, which is the following:

$$m \cdot \ddot{z} = \sum F = F_{hydr} + F_{PTO} \tag{3-3}$$

m is the WEC mass, F_{hydr} are the hydrodynamic forces and F_{PTO} is the force given by the power take-off of the device.

Here the hydrodynamic part of the model is described, therefore is explained in detail how to calculate the hydrodynamic force F_{hydr}, which the model has to calculate in order to get the WEC motion from equation ((3-3).
The hydrodynamic force acting on the WEC can be obtained by integrating the dynamic pressure (induced by the wave motion) over the WEC wet surface. The dynamic pressure can be obtained by the fluid velocity potential $\phi(x,y,z,t)$ as:

$$p^+ = -\varrho \frac{\partial \phi}{\partial t} \tag{3-4}$$

Which expressed in the frequency domain is, $p^+ = -\varrho i\omega\Phi$. Therefore, the hydrodynamic force can be estimated as:

$$F_{hydr} = \iint_A p^+ n_z dA = \iint_A -\varrho i\omega\Phi n_z dA \tag{3-5}$$

where A is the submerged WEC surface, n_z is the vertical component of the normal to the surface A.
By considering a partially submerged device with one degree of freedom (vertical motion along the z-axis), the **hydrodynamic forces** on the WEC can be expressed as follows:

$$F_{hydr} = -m^a\ddot{z} - \beta\dot{z} - kz + \frac{H}{2}F_E cos(\omega t + phase) \tag{3-6}$$

where m^a is the added mass, β is the hydraulic damping coefficient, k is the restoring coefficient, F_E and *phase* are respectively the amplitude and the phase of the excitation force given by a sinusoidal wave, with a wave height expressed by H. $z, \dot{z}, \ddot{z}$ are respectively the displacement, velocity and acceleration of the WEC.

By equating equations (3-5) and (3-6) the coefficient m^a, β and k can be obtained. Considering that, the hydrodynamic force is given by the sum of the following forces:

1. Force induced by the incident wave field F_I, even called Froud-Kryloff force
2. Diffraction force F_D (due to the wave diffraction around the WEC)
3. Radiation force F_R (due to the wave generated by the WEC motion)

The sum of F_I and F_D is called F_E, i.e. the excitation force of eq. (1.6). The radiation force F_R is given by the terms of added mass m^a, damping β and buoyancy restoring k, of eq. (1.6).

In the framework of linearized wave theory the incident, diffracted and radiated wave potential can be obtained solving the problem in two phases:

1. Fixed object and incident wave: to solve the incident and diffracted wave field
2. Object with a defined motion and absence of incident waves: radiated wave field

The fluid potential solved at these two phases enable to get the F_E, m^a, β and k coefficients. The phase 1 allows to provide the fluid velocity potential incident and diffracted, $\Phi = \Phi_I + \Phi_D$. The problem phase 1 can be mathematically written in the frequency domain as:

$\nabla^2\Phi = 0$ Laplace equation

$\Phi_z = \omega^2/g\Phi$ at the free surface

$\Phi_z = 0$ at the sea bottom (rigid and impermeable)

$\Phi_x + ik\Phi = \frac{2a'g}{\omega} k \frac{\cosh(k(h+z))}{\cosh(kh)}$ at the lateral boundary, condition of incident wave generation and free exit (3-7)

$\Phi_x + ik\Phi = 0$ free exit wave condition at the lateral boundary

$\Phi_n = 0$ at the WEC boundaries

The phase 2 allows analyzing the wave condition and the forces on the WEC, when it is moving with a given law of motion. The problem of phase 2 is expressed mathematically as:

$\nabla^2\Phi = 0$

$\Phi_z = \omega^2/g\Phi$ at the free-surface

$\Phi_z = 0$ at the sea bottom

$\Phi_n + ik\Phi = 0$ at lateral boundaries (3-8)

$\Phi_n = Z$ on WEC boundaries

The last condition imposes at the fluid particles adherent to the WEC to move with the same WEC velocity, $\Phi_n = Z$.
Given the solution Φ of problem (3-7), it is possible to solve the integral over the WEC surface of the wave induced pressure:

$$\iint_A -\varrho i\omega\Phi(\omega; x, y, z)n_z dA = F1 \qquad (3\text{-}9)$$

The excitation force in equation (3-6) can be obtained as follows:

$$F_E = \frac{H}{2}\overline{F1(\omega)}\cos(\omega t) \qquad (3\text{-}10)$$

Therefore, the hydraulic model is able to simulate a sea state as a monochromatic wave with a assigned value of wave height *H* and the frequency ω.
Given the solution Φ of problem **(3-8)**, by integrating the wave induced pressure on the WEC surface the sum of the forces on the WEC can be obtained

$$F2(\omega) = \iint_A -i\omega\varrho\Phi n_z dA \qquad (3\text{-}11)$$

The restoring force of the WEC is given by the buoyancy force, therefore the coefficient *k* can be obtained as:

$$k = \varrho g A_h \qquad (3\text{-}12)$$

where A_h is the WEC horizontal area.
The added mass coefficient m^a and the damping coefficient β, can be obtained from:

$$F_R(t) = Real\{F2(\omega)e^{-i\omega t}\} = -m^a\ddot{z}(t) - \beta\dot{z}(t) \tag{3-13}$$

$$\begin{aligned} &F2 = -i\omega m^a Z - \beta Z \\ &Real\left\{\frac{F2}{Z}\right\} = -\beta \\ &Imag\left\{\frac{F2}{Z}\right\} = -\omega m^a \end{aligned} \tag{3-14}$$

To summarize the solution of problem (3-1) and equation (3-3) provides the wave field and the WEC motion, if the power take-off of the device is computed by the electrical part of the model.

3.1.1.1 Numerical model applications

Preliminary simulations with the described 3D model have been carried out to achieve values of the hydrodynamics coefficients for different angular frequencies. The scope of these simulations has been to provide the input hydraulic parameter necessary to run the electrical model of stage 1.
As first analysis it has been reproduced one wave energy convertor of the point-absorber type, with one degree of freedom in the vertical movement (along z axis). The WEC has a buoy of cylindrical shape and it has been tested also by Bozzi et al, 2013 (Buoy 1 of Table 4 of the cited paper).
The numerical simulations have been carried out in a 3D domain 50 m large, 50 m long and 20 m deep. In the middle of the domain a cylinder with a diameter of 3 m and a height of 0.8 m, has been placed, with a submergence of 0.25 m.
In Figure 25 the domain of the simulation is represented, in red is the fluid volume and in blue is the WEC buoy.

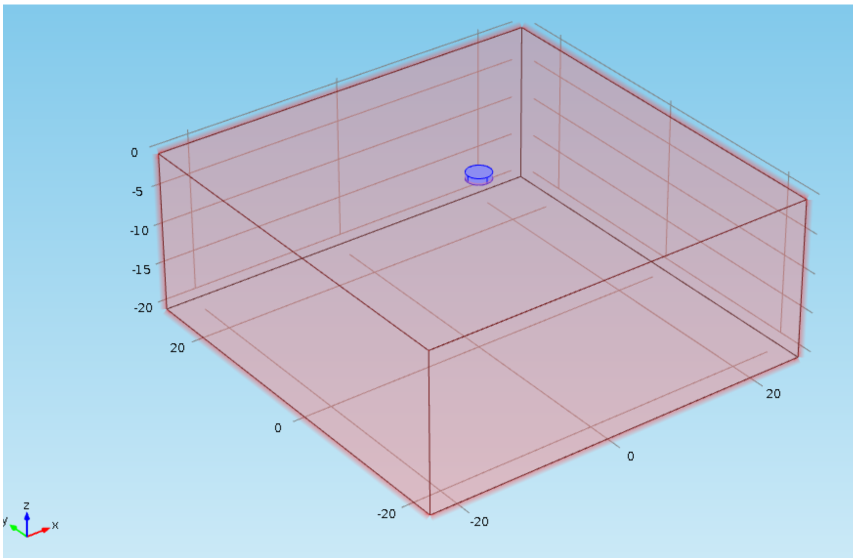


Figure 25: Domain of the three-dimensional numerical model

It has been tested the problem of incident waves and WEC buoy fixed, problem described by equations (3-7), and the problem of moving WEC buoy in the absence of incident waves (equations (**3-8**). Both problem has been solved for a range of angular frequency ω = 0.5, 1, 1.5, 2, 2.5, 3 rad/s.

In Figure 26 and in Table 16 the values of the hydrodynamic coefficients are reported.

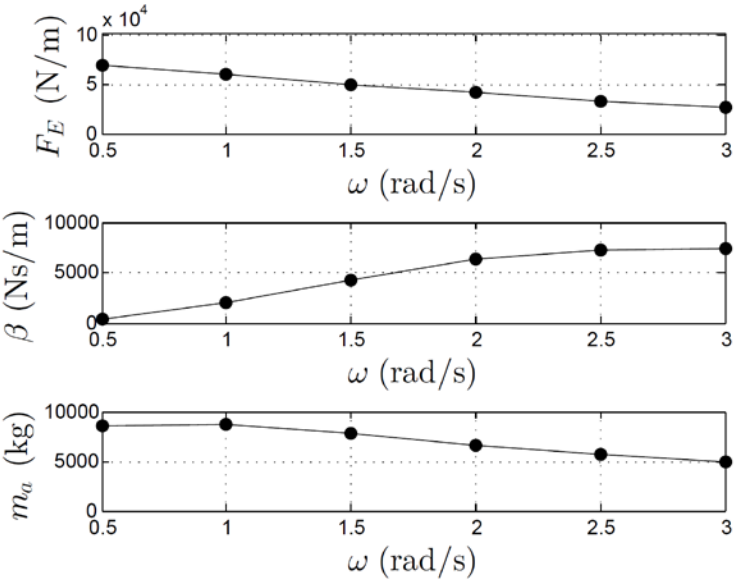


Figure 26: Hydrodynamic coefficients varying ω

ω (rad/s)	Phase F_E	F_E (N/m)	m^a (kg)	β (Ns/m)
0.5	2.169	68921	8567	331.3
1	0.529	60131	8764	1951
1.5	-2.499	48697	7831	4274
2	-0.351	41615	6561	6279.8
2.5	1.236	32974	5619	7292.8
3	2.774	26614	4966	7426

Table 16: Values of the hydrodynamic coefficients varying ω

These results are in accordance with those presented in Figure 3 of Bozzi et al. (2013). In Figure 27 and Figure 28 the results of solving respectively the problem (3-7) and (3-8) are presented in term of free-surface elevation.

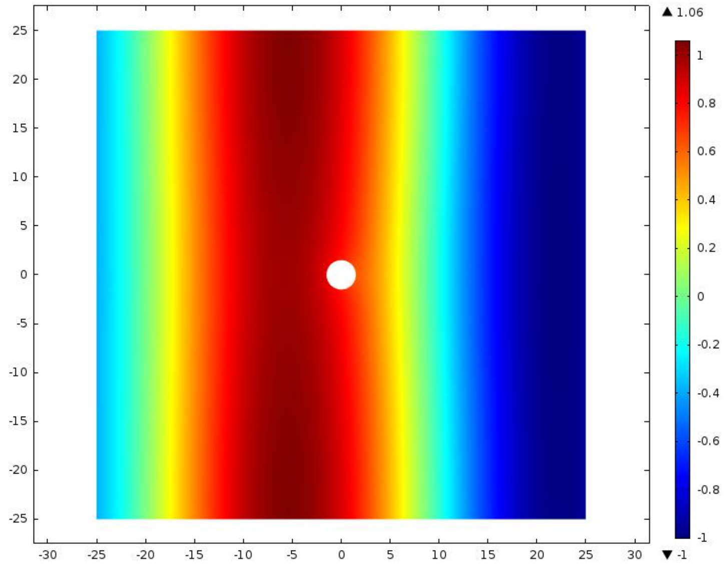


Figure 27: Free surface elevation for ω = 1 rad/s and incident wave amplitude of 1 m, entering into the domain from the left lateral boundary.

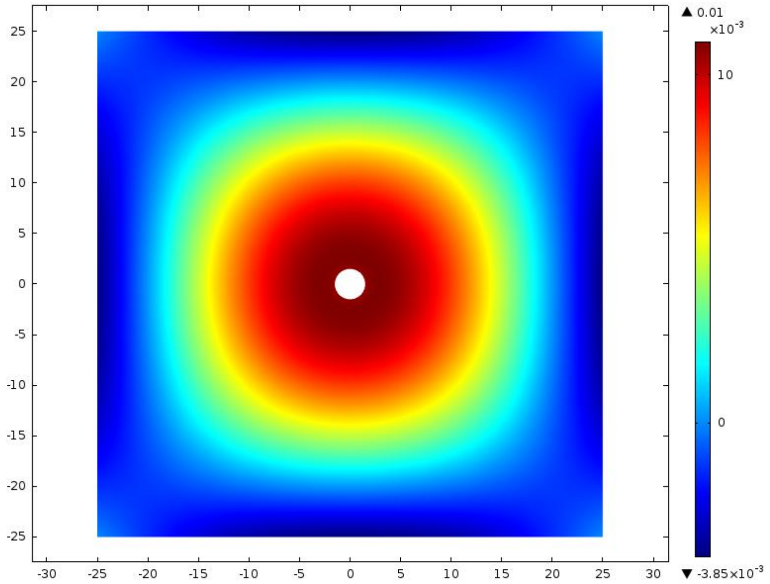


Figure 28: Free surface elevation in the absence of incident wave and with the moving WEC (velocity amplitude of 1 m/s and ω = 1 rad/s)

The same coefficients$F_E(\omega)$, $m^a(\omega)$ and $\beta(\omega)$ has been calculated solving the problems (3-7) and (3-8) in the case of 4 convertors.

As in the case of one single WEC, the excitation force in each device is obtained solving problem (3-7), fixed WEC buoys and unitary incident wave. To estimate the coefficients $m^a(\omega)$ and $\beta(\omega)$ in each WEC the problem (3-8) has been solved four times, by imposing the movement of one single device each time and keeping the others fixed.

The simulations are repeated for a range of frequencies ω = 0.3 rad/s up to ω = 1.9 rad/s, with a step of 0.2 rad/s. The type of wave energy converters simulated is the same of the case of one single device.

All the simulations have been performed in 3 different configuration layout: 1) row configuration; 2) column configuration and 3) 2x2 configuration. In Figure 29, Figure 30 and Figure 31 the three configurations are presented, showing in green the boundary where the incident waves are enter into the domain.

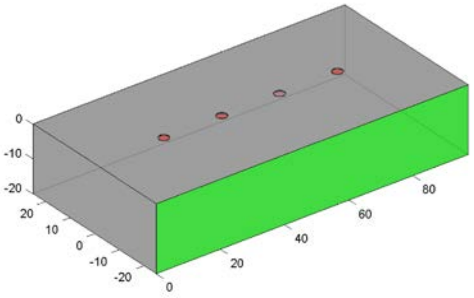


Figure 29: Domain of the 3D numerical model with 4 WECs in "row" configuration. In green is highlighted the boundary of incident wave entrance.

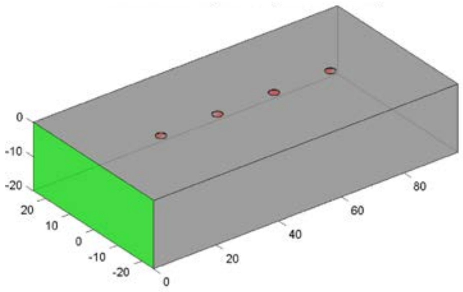


Figure 30: Domain of the 3D numerical model with 4 WECs in "column" configuration. In green is highlighted the boundary of incident wave entrance.

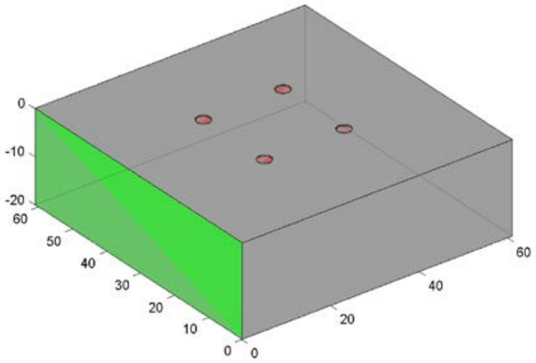


Figure 31: Domain of the 3D numerical model with 4 WECs in "2x2" configuration. In green is highlighted the boundary of incident wave entrance.

Centro del WEC	**WEC1**	**WEC2**	**WEC3**	**WEC4**
x	21.5	39.5	57.5	75.5
y	0	0	0	0
z	-0.25	-0.25	-0.25	-0.25

Table 17: Position of the lowest center of the 4 WECs cylindrical buoys in the configurations of Figure 29 and Figure 30.

In Table 17, are reported the coordinates of the lowest center of the 4 cylindrical WEC buoys for the "row" and "column" configuration (Figure 29 and Figure 30 respectively). While the positions of the WECs buoys in the "2x2" configuration are reported in Table 18.

Centro del WEC	**WEC1**	**WEC2**	**WEC3**	**WEC4**
x	21.5	39.5	39.5	21.5
y	21.5	21.5	39.5	39.5
z	-0.25	-0.25	-0.25	-0.25

Table 18: Position of the lowest center of the 4 WECs cylindrical buoys in the configuration of Figure 31.

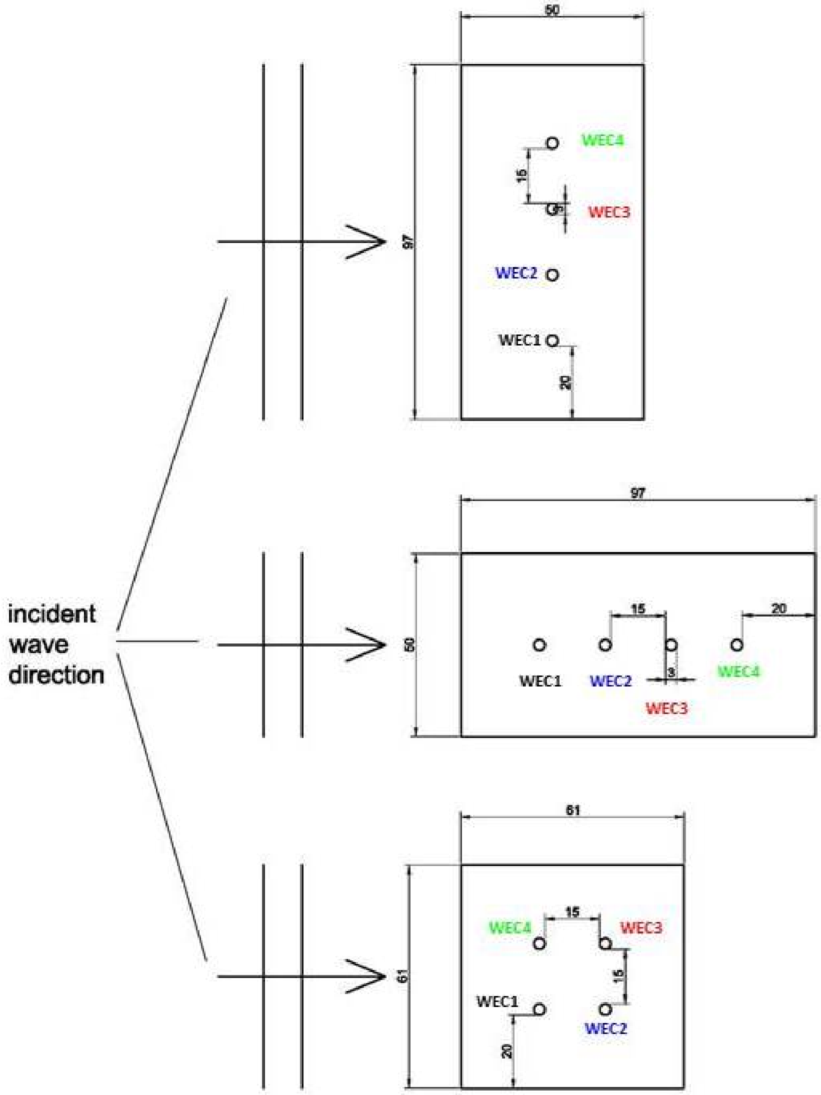


Figure 32: Plan view of the three configurations, with details of dimensions.

In the following are presented the values of the coefficients F_E, for each WECs and for the given frequencies. Respectively for the three configurations, results are shown in Figure 33, Figure 37, Figure 41 and Table 19, Table 20 and Table 21.

The values of the coefficients m^a are shown in graph, for the three configurations respectively in Figure 34, Figure 38 and Figure 42.

The values of the coefficients β are shown in graph, for the three configurations respectively in Figure 35, Figure 39 and Figure 43.

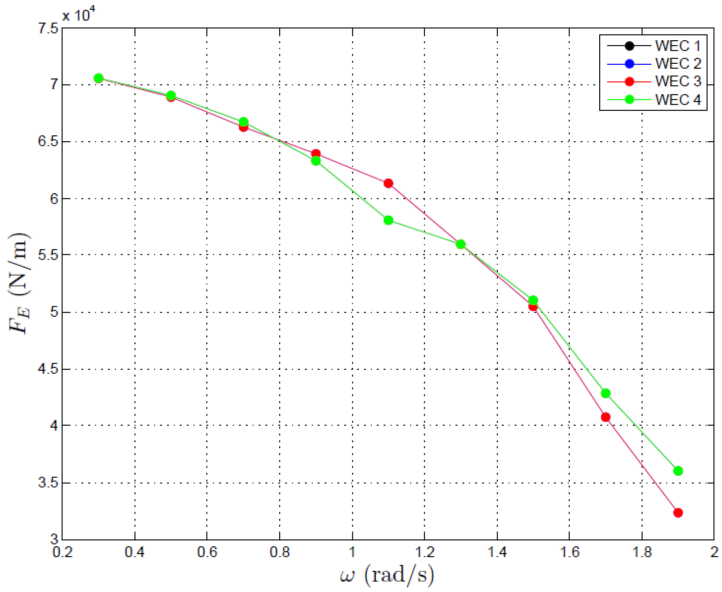


Figure 33: Amplitude of the excitation force for a unitary incident wave amplitude entering in the domain of Figure 32 (upper plot "row" configuration). In black values of the WEC1, in blue values of the WEC2, in red values of the WEC3 and in green values of the WEC4. The values of the WEC1 coincide with those of WEC4 and that of WEC2 with those of WEC3.

F_E (N/m)	ω(rad/s)								
	0.3	0.5	0.7	0.9	1.1	1.3	1.5	1.7	1.9
WEC1	70559.61	69017.71	66704.94	63285.99	58059.34	55942.66	51012.11	42841.07	36020.23
WEC2	70525.47	68882.18	66241.04	63904.94	61305.85	55939.43	50488.19	40749.77	32341.20
WEC3	70525.30	68881.76	66240.46	63904.06	61308.60	55941.53	50478.92	40751.08	32342.29
WEC4	70559.36	69018.07	66704.00	63285.92	58058.83	55945.37	51020.15	42843.53	36027.11

Table 19: Values of amplitude of the excitation force for a unitary incident wave amplitude entering in the domain of Figure 32 (upper plot "row" configuration).

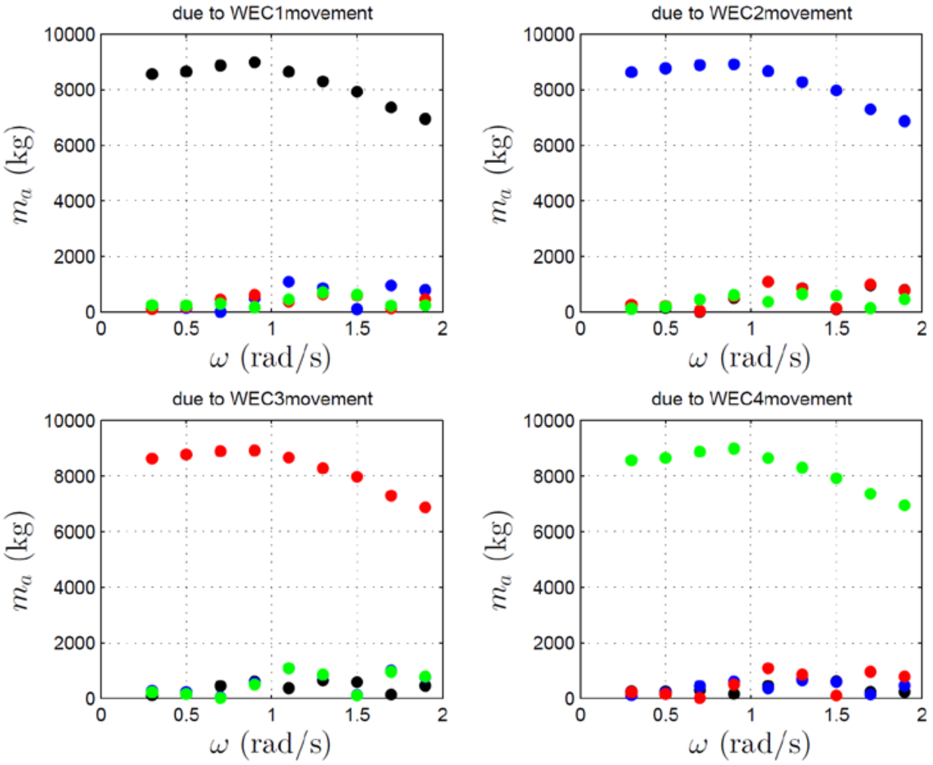


Figure 34: Added mass coefficients ma for WEC1 (black), WEC2 (blue), WEC3 (red), WEC4 (green) with frequency, for the “row” configuration (upper plot of Figure 32). Each subplot refers to the simulation with the imposed motion to each single WEC.

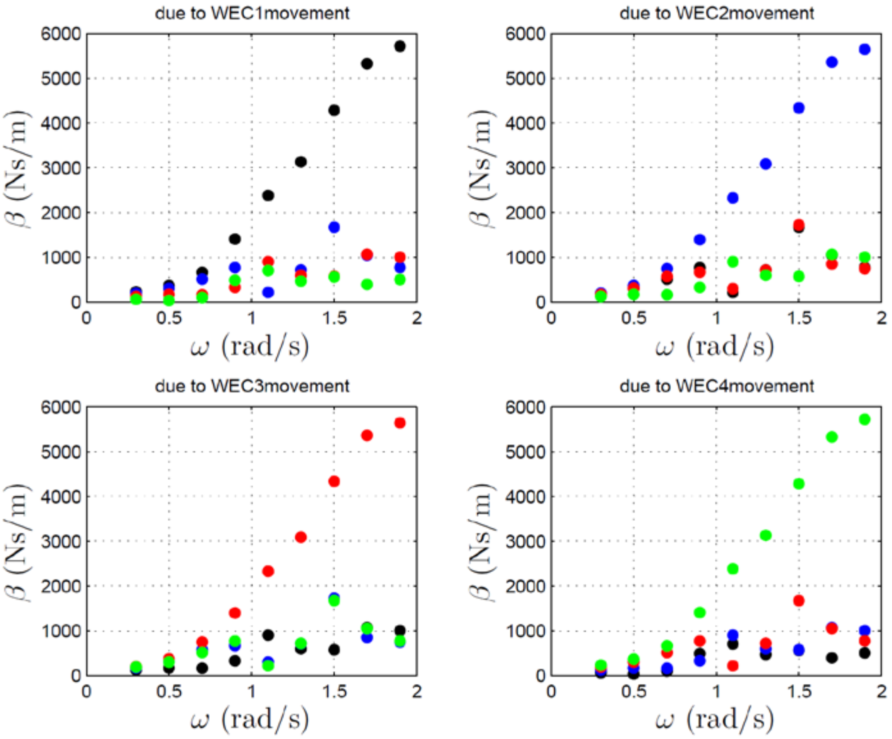


Figure 35: Added mass coefficients m^a for WEC1 (black), WEC2 (blue), WEC3 (red), WEC4 (green) with frequency, for the “row” configuration (upper plot of Figure 32). Each subplot refers to the simulation with the imposed motion to each single WEC.

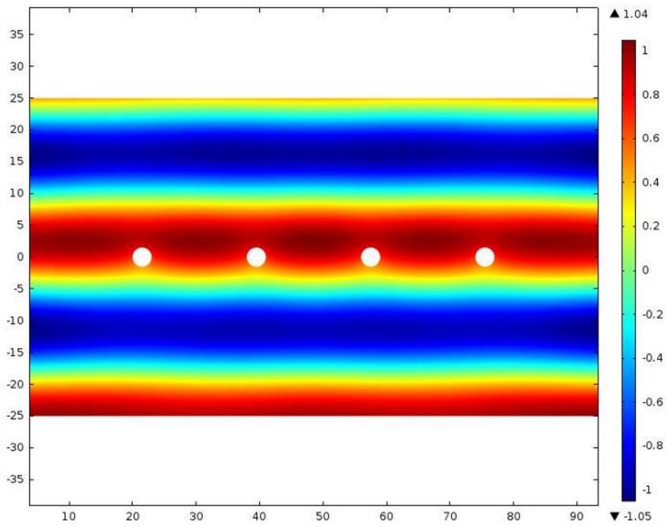


Figure 36: Free surface elevation for ω = 1 rad/s and incident wave amplitude of 1 m, entering from the bottom lateral boundary into the domain with 4 WECs in "row" configuration.

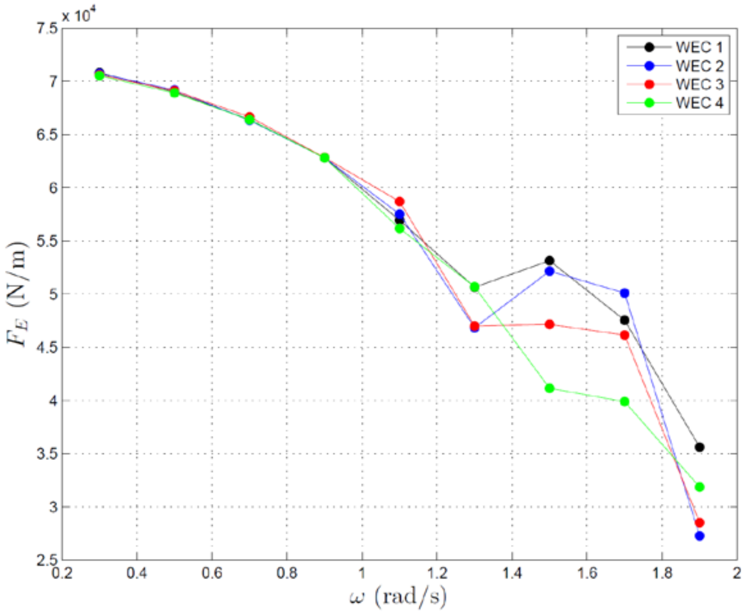


Figure 37: Amplitude of the excitation force for a unitary incident wave amplitude entering in the domain of Figure 32 (upper plot "row" configuration). In black values of the WEC1, in blue values of the WEC2, in red values of the WEC3 and in green values of the WEC4.

F_E (N/m)	ω (rad/s)								
	0.3	0.5	0.7	0.9	1.1	1.3	1.5	1.7	1.9
WEC1	70807.21	68999.85	66411.18	62811.72	56930.73	50643.40	53129.60	47534.74	35601.21
WEC2	70718.87	69172.72	66318.39	62808.53	57508.81	46826.33	52150.58	50090.46	27267.52
WEC3	70601.06	69097.59	66657.09	62817.35	58697.12	46994.42	47146.01	46141.94	28503.86
WEC4	70524.01	68899.36	66377.39	62799.47	56158.45	50690.64	41134.37	39886.67	31850.29

Table 20: Values of amplitude of the excitation force for a unitary incident wave amplitude entering in the domain of Figure 32 (middle plot "column" configuration).

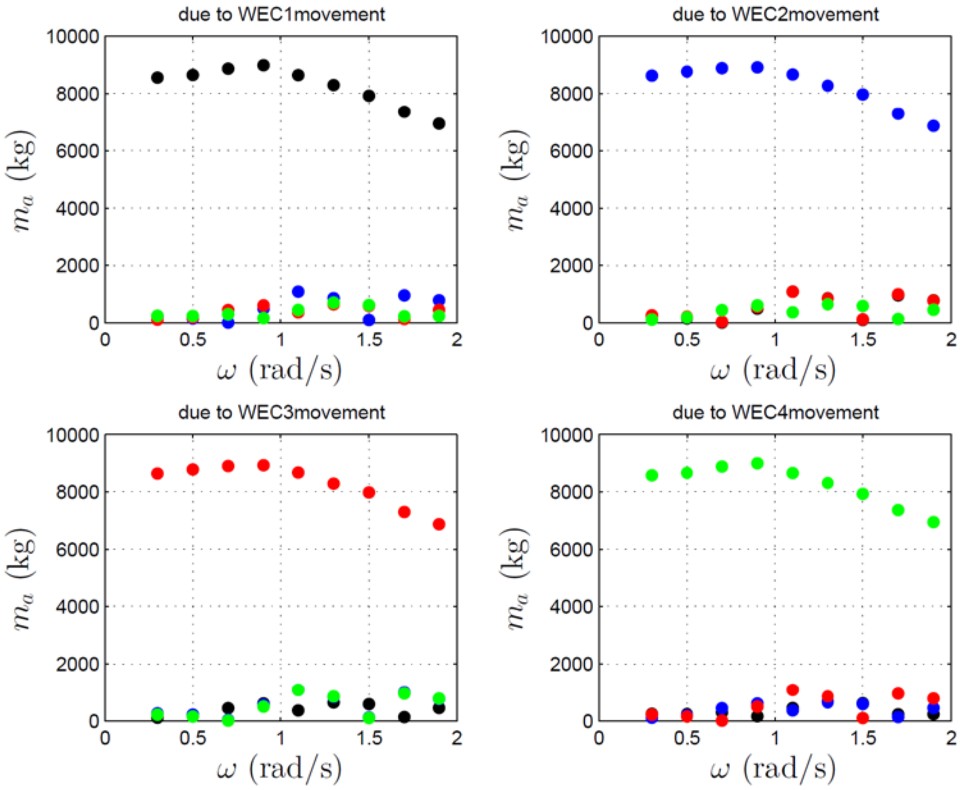


Figure 38: Added mass coefficients ma for WEC1 (black), WEC2 (blue), WEC3 (red), WEC4 (green) with frequency, for the "column" configuration (middle plot of Figure 32). Each subplot refers to the simulation with the imposed motion to each single WEC.

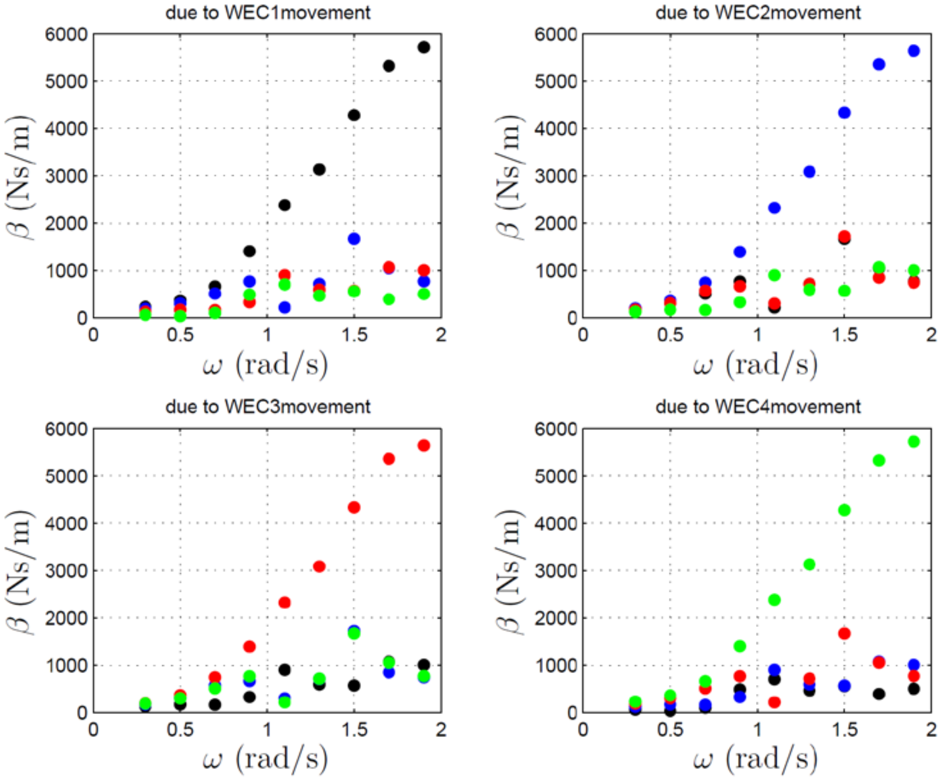


Figure 39: Added mass coefficients m^a for WEC1 (black), WEC2 (blue), WEC3 (red), WEC4 (green) with frequency, for the "column" configuration (middle plot of Figure 32). Each subplot refers to the simulation with the imposed motion to each single WEC.

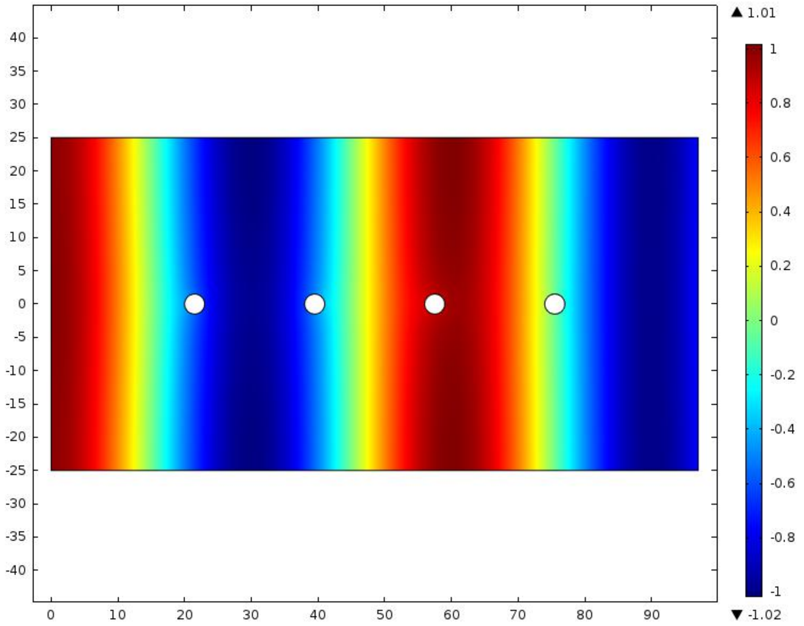


Figure 40: Free surface elevation for ω = 1 rad/s and incident wave amplitude of 1 m, entering from the left lateral boundary into the domain with 4 WECs in "column" configuration.

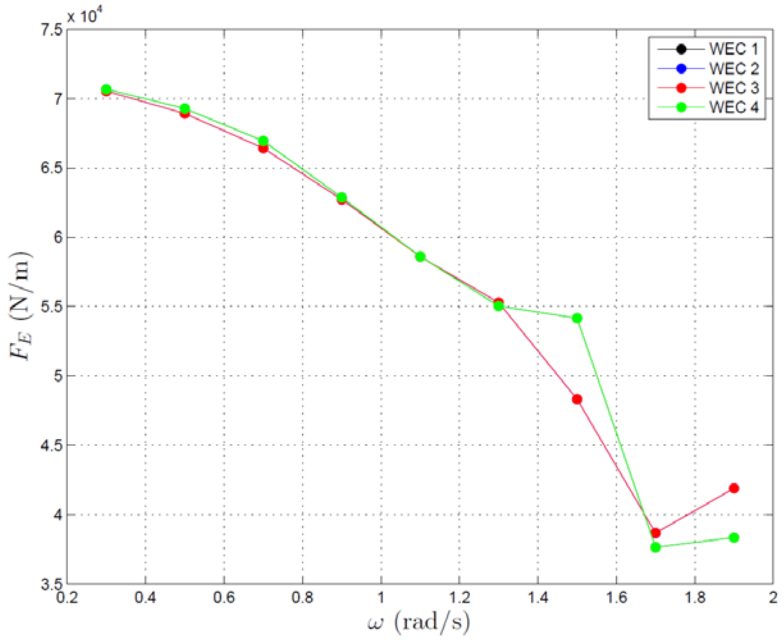


Figure 41: Amplitude of the excitation force for a unitary incident wave amplitude entering in the domain of Figure 32 (upper plot "row" configuration). In black values of the WEC1, in blue values of the WEC2, in red values of the WEC3 and in green values of the WEC4. The values of the WEC1 coincide with those of WEC4 and that of WEC2 with those of WEC3.

F_E (N/m)	**ω (rad/s)**								
	0.3	0.5	0.7	0.9	1.1	1.3	1.5	1.7	1.9
WEC1	70667.91	69277.02	66938.37	62864.77	58616.14	55044.45	54155.26	37655.79	38354.96
WEC2	70530.31	68917.80	66419.99	62722.37	58600.95	55289.07	48323.29	38670.02	41907.29
WEC3	70530.12	68917.59	66419.95	62721.25	58596.90	55293.44	48328.69	38673.22	41895.20
WEC4	70668.06	69277.24	66939.86	62865.71	58615.94	55040.19	54157.00	37657.00	38356.26

Table 21: Values of amplitude of the excitation force for a unitary incident wave amplitude entering in the domain of Figure 32 (lower plot "2x2" configuration).

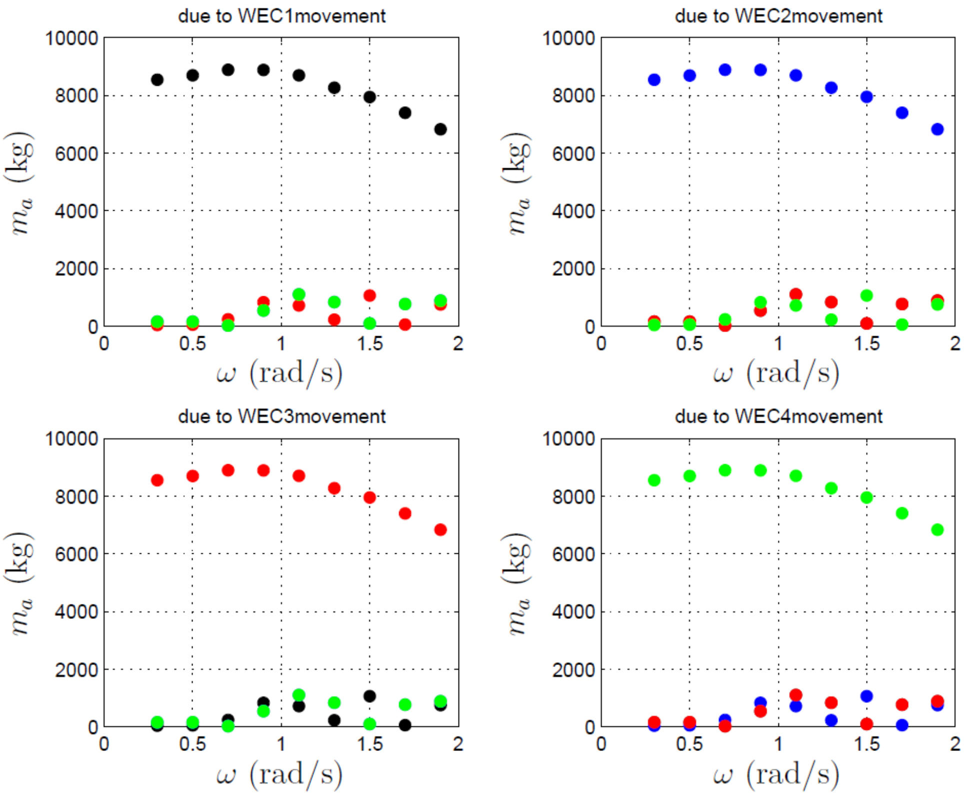


Figure 42: Added mass coefficients ma for WEC1 (black), WEC2 (blue), WEC3 (red), WEC4 (green) with frequency, for the "2x2" configuration (lower plot of Figure 32). Each subplot refers to the simulation with the imposed motion to each single WEC.

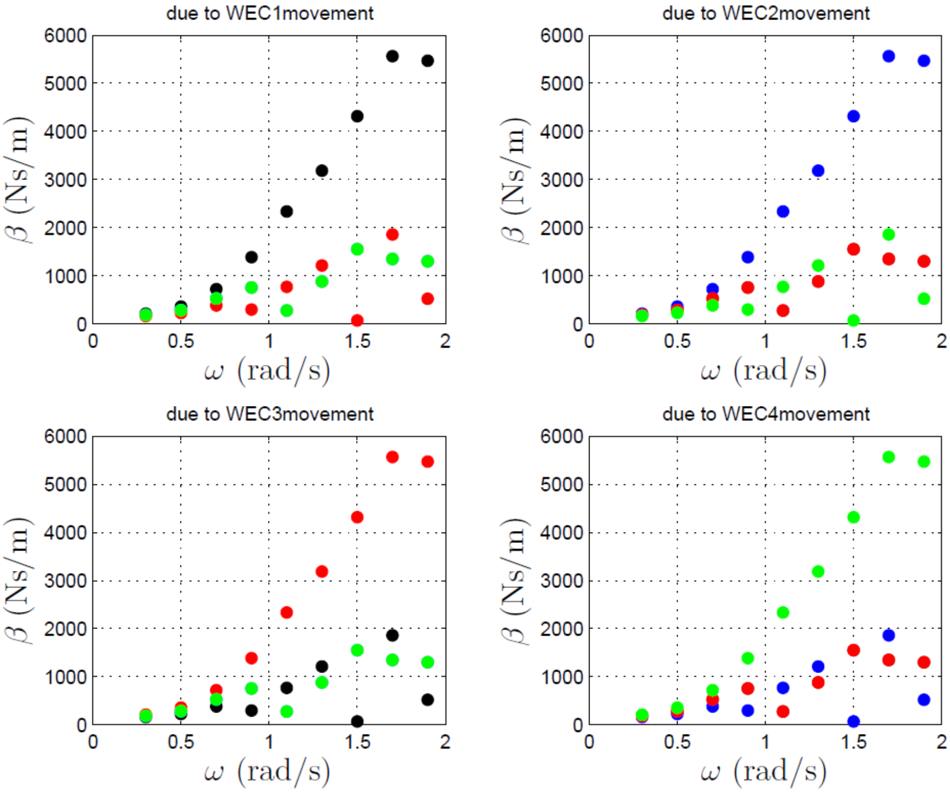


Figure 43: Added mass coefficients m^a for WEC1 (black), WEC2 (blue), WEC3 (red), WEC4 (green) with frequency, for the "2x2" configuration (lower plot of Figure 32). Each subplot refers to the simulation with the imposed motion to each single WEC.

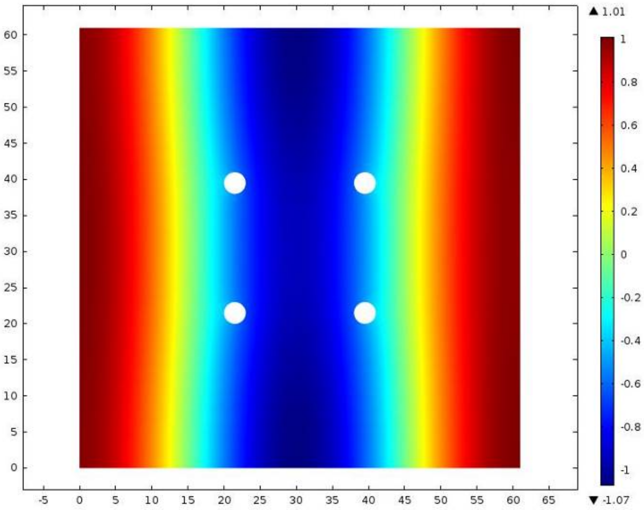


Figure 44: Free surface elevation for ω = 1 rad/s and incident wave amplitude of 1 m, entering from the left lateral boundary into the domain with 4 WECs in "2x2" configuration.

3.1.2 Hybrid numerical model

Here it is described a numerical model that has been thought in order to reduce the computational times when reproducing a WEC battery over a large sea area. The model is based on a hybrid concept modeling, because it couples solutions at domains of three and two dimension.

A detailed 3D computation is solved around one wave energy device in a small cylindrical domain, with height equal to the water depth and diameter equal to around double of the horizontal dimension of the WEC. Given an arbitrary incident wave and given the WEC specifics, the model is able to return the complex three-dimensional wave field and the device motion, solving the problem (3-1) together with the equation of motion (3-3). Then a depth-integrated equation is solved at the free-surface, in a two-dimensional horizontal model (2DH) which contains around each WECs circular holes, with the same diameter of the 3D cylindrical domain. As can be seen in Figure 45 the detailed 3D simulation (in blue on the left plot) is only around one WEC and has to be run previously; then, in the hypothesis of a battery of identical WECs, the simulation in the 2D domain (in red on the right plot) can be run. The model is able to reproduce many simulations, varying the wave conditions or the WECs layout.

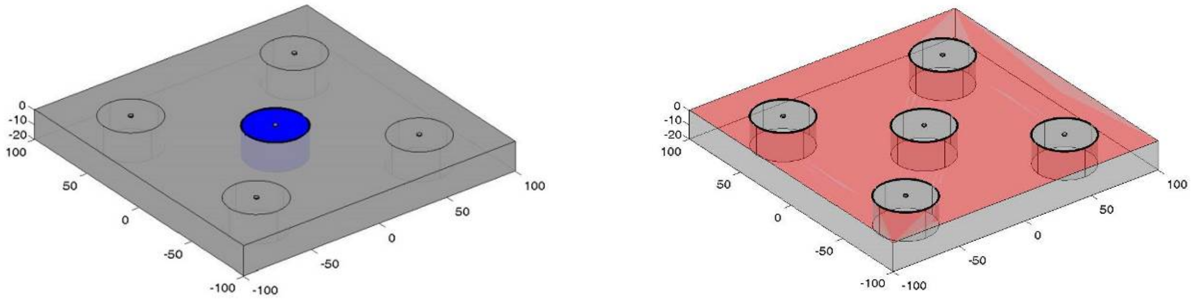


Figure 45: 3D (left plot) and 2D (right plot) domains of the hybrid numerical model. For a 200mx200m sea area, 20m of water depth, with 5 WECs.

The 2DH simulation is able to accurately reproduce the wave propagation for a constant depth, or mildly sloped area, solving the Helmholtz equation (or the mild-slope equation) together with external boundary conditions, which allow the entrance of the incident wave field and the wave free exit. Particular attention has to be paid at the internal boundary conditions (black circles in the right plot of Figure 45). The condition imposed at these boundaries is the key point of the hybrid model, because it match the 3D with the 2DH solutions.

At the internal circular boundaries of the 2DH domain, the condition must allow the entrance and the exit of small amplitude waves; this condition is expressed as follows:

$$\Psi_n + \alpha(x,y,\Psi,\Psi_n)\Psi = G(x,y,\Psi,\Psi_n) \qquad (3\text{-}15)$$

where $\Psi(x,y,\omega)$ is the fluid velocity potential at the free-surface and α is an absorption/reflection coefficient, while G is a generic generation term. These coefficients vary along the circular boundary and are functions of the fluid velocity potential and its normal derivative at each point of the boundary. They can be obtained by the solution of the 3D model around one WEC, and therefore the continuity of the fluid in the two domains (3D around the WEC and 2D in the surrounding area) is ensured.

Let consider a vertical section of a constant depth area with one single WEC, in order to more easily explain how the hybrid model match the 3D and 2D domains. Referring to Figure 46 points A and B represent the internal boundaries of the 2DH simulation (dashed lines domain).

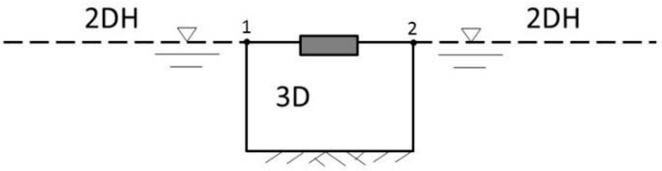


Figure 46: Sketch of the hybrid numerical domain for a vertical section of constant depth sea with one WEC

The problem (3-1) and equation (3-3) are previously solved in the 3D domain, imposing a unitary wave amplitude entrance at the lateral left boundary and free exit at the right lateral boundary. From its solution $\Phi(x, y, z, \omega)$ and $\Phi_n(x, y, z, \omega)$ at the points A and B the coefficients α and G can be estimated as follows:

$$\begin{aligned} &\Psi_n^1 + \alpha^{11}\Psi^1 = \alpha^{21}\Psi^2 \\ &\Psi_n^2 + \alpha^{22}\Psi^2 = \alpha^{12}\Psi^1 \end{aligned} \tag{3-16}$$

As said the generation term G is function of the fluid velocity potential therefore in (3-16) G in each boundary has been expressed as the product of a coefficient α and the fluid potential at the other boundary.

The resulting unknown coefficients are 4, α^{ij} with both $i, j = 1{,}2$, therefore the 3D simulation has to be run twice by varying the boundary condition of wave entrance, in order to get two equations at point 1 and two equations at point 2.

$$\begin{pmatrix} \Psi_n^{1,1} \\ \Psi_n^{1,2} \\ \Psi_n^{2,1} \\ \Psi_n^{2,2} \end{pmatrix} = \begin{bmatrix} \Psi^{1,1} & \Psi^{2,1} & 0 & 0 \\ \Psi^{1,2} & \Psi^{2,2} & 0 & 0 \\ 0 & 0 & \Psi^{1,1} & \Psi^{1,1} \\ 0 & 0 & \Psi^{1,1} & \Psi^{1,1} \end{bmatrix} \begin{pmatrix} \alpha^{11} \\ \alpha^{21} \\ \alpha^{12} \\ \alpha^{22} \end{pmatrix} \tag{3-17}$$

In the system (3-17) $\Psi^{i,j}$ represents the fluid potential at the boundary i, for the j 3D simulation. Solving the system (3-17) with the 3D solutions allows to estimate the vector of unknown coefficients α.

In the procedure when the hybrid model is applied to a real 3D-2D domain, i.e. not a vertical section, the internal boundaries are no more just two, but a number N of segments on which the circular boundary is divided. The system to get the coefficients at the N internal boundary is expressed as follows:

$$\overline{\Psi_n} = \overline{\overline{\Psi}} \cdot \bar{\alpha} \tag{3-18}$$

Where $\overline{\Psi_n}$ is the vector that contain the derivative of fluid velocity potential to the normal of each boundary segment; $\overline{\Psi}$ is the vector that contain the fluid velocity potential in each boundary segment.

$\overline{\Psi_n}$ and $\overline{\Psi}$ are vectors of *NxN* elements $\Psi^{i,j}$ where $i = 1,..,N$ represents the boundary segment where the potential and its derivative are calculated, while $j = 1,..,N$ is an index of the 3D simulation.

$\bar{\alpha}$ is the unknown vector of coefficient, it contains *NxN* element that can be named as α^{ij} where $i, j = 1,..,N$. When $i = j$ the coefficient represents the absorbtion/reflection coefficient of the i^{th} segment of the boundary; when $i \neq j$ it represents the generation coefficient at the j^{th} segment, given by the fluid potential contribution of the i^{th} segment.

Once the α coefficients are estimated by the 3D simulations, the model solves the wave field in the 2D domain, by applying the following equations and boundary conditions:

$$\nabla^2\Psi + k^2\Psi = 0$$

$$\Psi_n + ik\Psi = \frac{2a'g}{\omega}k \quad \text{at the external boundary}$$

$$\Psi_n^j + \alpha^{jj}\Psi^j = \sum_{i=1}^{N} \alpha^{ij}\Psi^i \quad \text{at the internal } j^{th} \text{ boundary} \tag{3-19}$$

Now it will be presented the results of all the simulations carried out with the hybrid model. For all the simulations the WEC device is the one with a cylindrical buoys of the same characteristic described in the previous section. The hybrid model has been compared each time with the solution of the fully 3D model (3-1).

The hybrid model has been preliminary tested for a vertical section of constant water depth and with the presence of one WEC. In Figure 47 are shown the results at the free-surface (*z = 0*) in terms of absolute value and phase function of the fluid velocity potential. The domain covers an area of *200 m*, with constant water depth of 20 m. The WEC has been positioned with the lowest center in coordinates (*x = 0, z= -0.25 m*). In the whole domain the 3D problem has been solved, and results are plotted by the black line in Figure 47. The hybrid model has been solved, previously computing the 3D simulation in the small area $x \in (-50, 50)$ and $z \in (0, -20)$ in order to get the vector of the unknown coefficients; then by solving the problem (3-19) in the 2D domains $x \in (-100, -50)$ and $x \in (50, 100)$ for $z = 0$.

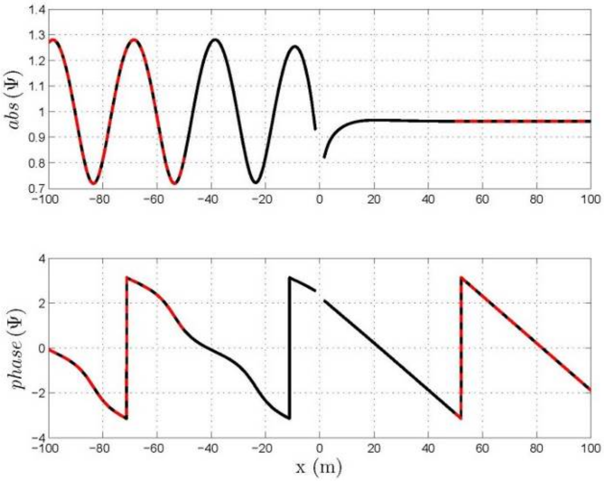


Figure 47: Absolute value and phase function of the fluid velocity potential at the free-surface, obtained by the hybrid model (red dashed lines) and by the fully 3D model (black lines) solved for comparison. Both models are

applied to a vertical section of constant depth area (h = 20 m) for a monochromatic incident wave (entering from left boundary) of H = 1 m and ω = 1 rad/s .

Once the hybrid model has been tested for a vertical section, simulation in 3D area with one WEC has been carried out. Again the hybrid model has been compared with the fully 3D model in the whole domain. The domain is *400x400x20* m, and the WEC is located in the middle. In the hybrid model a cylinder with a diameter of 50 m and 20 m high, located around the WEC, represents the 3D domain.

In Figure 48 are shown the results of the two model (3D on the left plot, hybrid model on the right plot) in terms of free-surface elevation. An incident wave (*H = 1m, ω = 1 rad/s*) was forced to enter into the domain from the right lateral boundary.

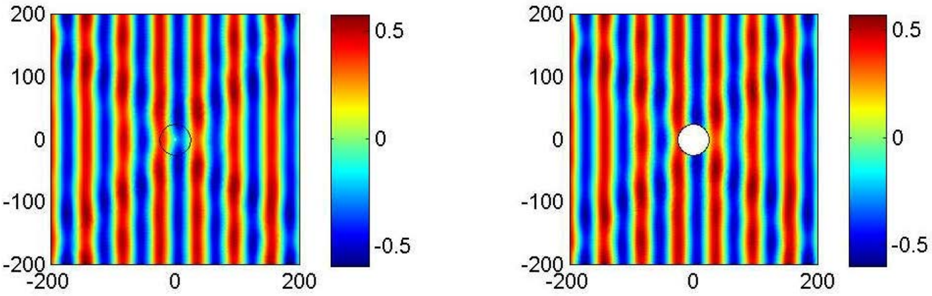


Figure 48: Free-surface elevations computed from the fully 3D model (left plot) and the hybrid model (right plot). A incident wave (H = 1m, ω = 1 rad/s) is entering from the right lateral boundary into the domain of constant depth area of h = 20 m with 1 WECs buoy.

For the same simulations results at the section *y = 0*, has been plotted in Figure 49. The comparison between 3D and hybrid model can be seen to be in very good agreement.

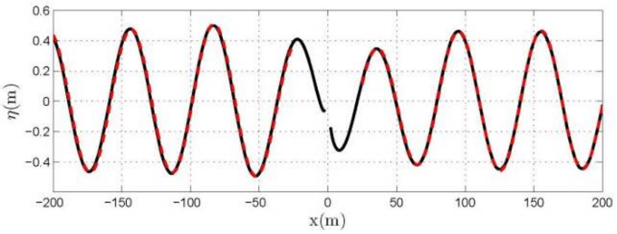


Figure 49: Free-surface elevations at the section y = 0, of the domain of Figure 48, computed from the fully 3D model (black line) and the hybrid model (red dashed line).

For the same simulations results are also shown in term of wave height distribution, in the whole free-surface (Figure 50) and in the section *y = 0* (Figure 51).

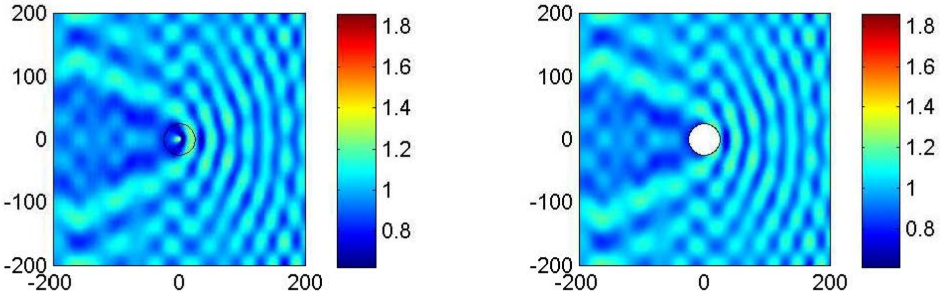


Figure 50: Wave height field computed from the fully 3D model (left plot) and the hybrid model (right plot). A incident wave (H = 1m, ω = 1 rad/s) is entering from the right lateral boundary into the domain of constant depth area of h = 20 m with 1 WEC buoy.

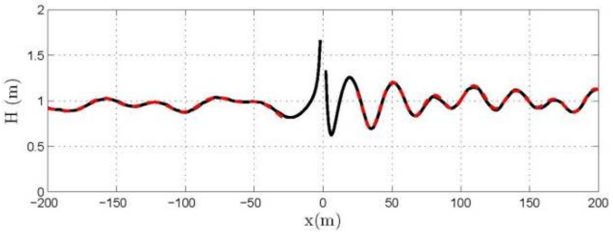


Figure 51: Wave height at the section y = 0, of the domain of Figure 48, computed from the fully 3D model (black line) and the hybrid model (red dashed line).

Then the hybrid model has been implemented in the presence of 5 WECs buoys: the wave field which moves each converter device it depends on the movement of the other devices. The perfect agreement between the 3D model results and the hybrid ones confirm the possibility of applying the hybrid model with different number of WECs and different layout. It is worth to mention that the 3D simulations solved around one WEC provide the α coefficients, which are valid for all the circular internal boundaries.

In Figure 52 and in Figure 54 are shown respectively the free-surface elevation and the wave height distribution on the plane *x-y* at *z = 0*. While in Figure 53 and Figure 55 are shown the results at to sections.

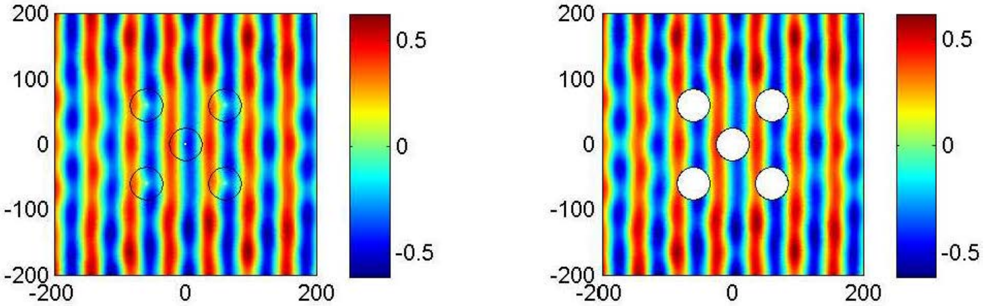


Figure 52: Free-surface elevations computed from the fully 3D model (left plot) and the hybrid model (right plot). A incident wave (H = 1m, ω = 1 rad/s) is entering from the right lateral boundary into the domain of constant depth area of h =20 m, with 5 WECs buoys.

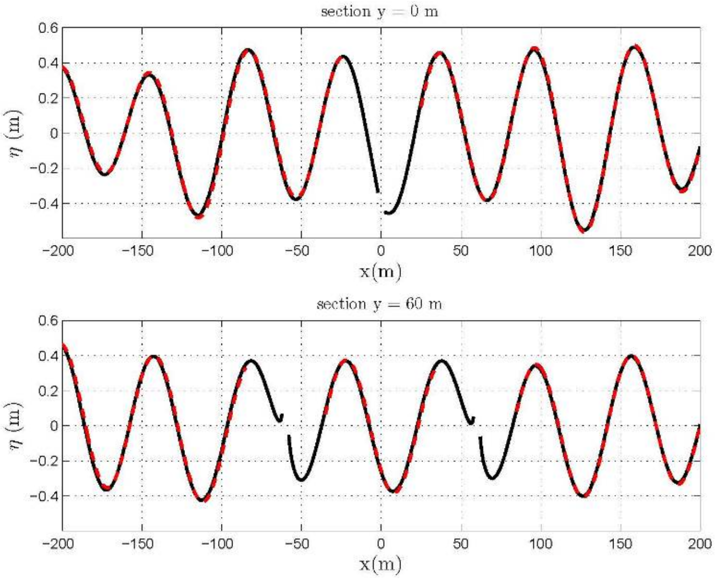


Figure 53: Free-surface elevations at the section y = 0 (upper plot) and y = 60 m (lower plot), of the domain of Figure 52, computed from the fully 3D model (black line) and the hybrid model (red dashed line).

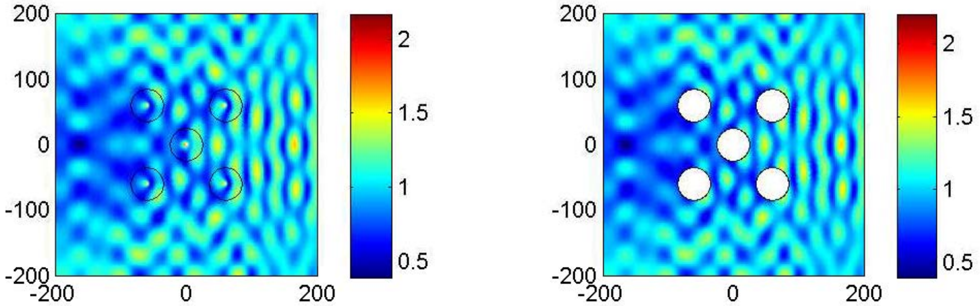


Figure 54: Wave height field computed from the fully 3D model (left plot) and the hybrid model (right plot). A incident wave (H = 1m, ω = 1 rad/s) is entering from the right lateral boundary into the domain of constant depth area of h =20 m, with 5 WECs buoys.

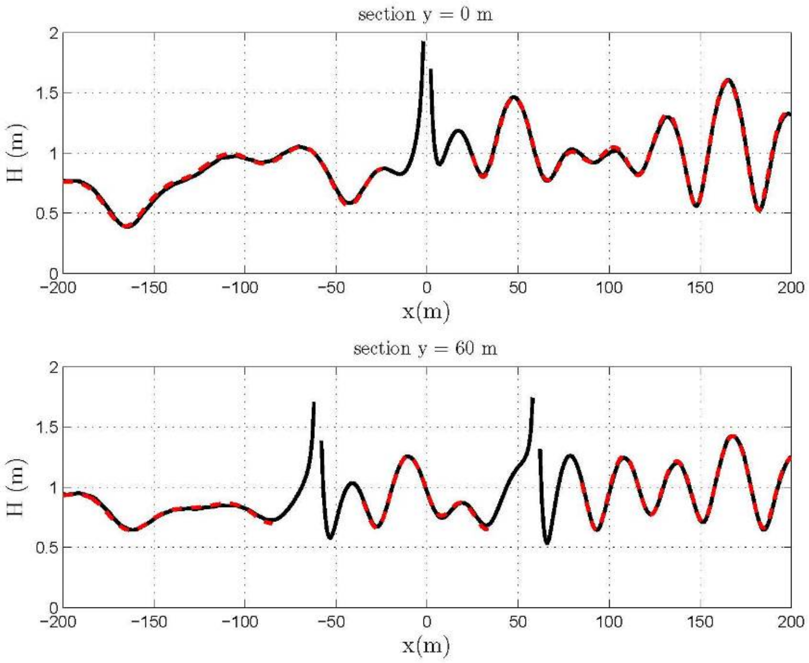


Figure 55: Wave height at the section y = 0 (upper plot) and y = 60 m (lower plot), of the domain of Figure 54, computed from the fully 3D model (black line) and the hybrid model (red dashed line).

To solve the 3D model with 5 WECs it takes around 41 s, the mesh consists in 83296 tetrahedral elements, with a number of degree of freedom of 123837; while the hybrid model takes around 21 s, the mesh consists in 5482 linear triangular elements and the number of degree of freedom is 11320.

3.2 Electrical models – Dynamic models and system stability analysis

In the following subparagraphs the main electrical aspects concerning integration of wave energy converters are described according to the modeling approach presented at the beginning of Chapter 3.

3.2.1 Wave to wire model of an array of WECs of point absorber type (Modeling stage 1)

A numerical model of the coupled buoy-electrical drive system able to simulate the behavior of an array of wave energy converters of point absorber type under regular waves of different wave heights and periods is presented. The array is thought to be composed by equal WECs.
The hydrodynamic forces, including excitation force, radiation impedance and hydrostatic force acting on each converter, are calculated by linear potential wave theory as indicated in section 3.1.
Each wave energy converter is modeled as a single body system with one degree of freedom along the vertical axis (heave mode), therefore the floating body dynamics are determined by solving the following equation of motion, which combines the hydrodynamic forces $F_H(t)$ and the resistance forces $F_{PTO}(t)$ due to the PTO system:

$$m\cdot\ddot{z}(t)=F_H(t)+F_{\mathrm{PTO}}(t)-\mathrm{F_k}(t) \qquad (3\text{-}20)$$

where m is the total mass of each system, $\ddot{z}(t)$ represents the vertical acceleration of each WEC and $FK(t)$ is the elastic force of the spring system eventually attached to the translator, which is calculated by

$$\mathrm{F_k}(t)=\mathrm{K}\cdot\mathrm{z}(t) \qquad (3\text{-}21)$$

where K is the elastic constant of the spring.

The hydrodynamic forces on the heaving buoy are calculated by:

$$F_H(t)=-m_a\ddot{z}(t)-\beta\dot{z}(t)-\mathrm{k}z(t)+0.5\ F_{\mathrm{E}}Hcos(\omega t+\alpha) \qquad (3\text{-}22)$$

where $z(t)$ is the vertical coordinate at time, t measured with respect to the buoy equilibrium position in calm seas, $\dot{z}(t)$ is the vertical speed. The four terms on the right side of the equation represent the different forces acting on the buoy: (1) added inertial force, accounting for the fluid volume moving with the buoy, where m^a is the added mass; (2) radiation damping force, due to the waves created by buoy oscillations, where β is the radiation damping coefficient; (3) hydrostatic restoring force, where k is the hydrostatic coefficient; and (5) vertical component of the excitation force, due to the incident waves on the assumedly fixed body, where Fe is force amplitude, H and ω are, respectively, wave height and frequency and α is the phase angle between the wave and the wave-induced heaving force.

3.2.2 Interfacing control of an "array-equivalent WEC" (Modelling stage 2)

3.2.2.1 Regulation principle

The reference scheme of the DC side of a PTO having the input power from the electrical generator P_{wave} and supplying the grid with the power P_{inv}, is reported in Figure 56.

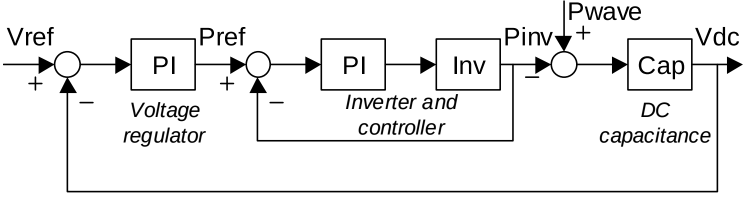


Figure 56. Principle scheme of the PTO inverter control

The inverter is supposed to be controlled by a power regulator of PI type, which provides it exchange the power P_{ref} with the grid. The output of the inverter PI regulator is the phase shift of the fundamental voltage the inverter generates with respect to the grid voltage. Considering that, the interface between the inverter bridge and the grid is made by the filters, which at rated frequency, show an inductive behaviour, the inverter is modelled as a simple algebraic transfer function given by:

$$P = \frac{V_{inv} V_{grid}}{X_{filter}} \sin \vartheta \qquad (3\text{-}23)$$

in which V_{inv} and V_{grid} are the amplitude of inverter fundamental voltage and grid voltage, X_{filter} is the reactance of the inverter filter and ϑ is the phase shift between the two voltages.
In relative values, we can assume both voltages have unitary amplitude, while a 0.1p.u. value can be assumed for the reactance. For small phase shift, we can also assume $\sin\vartheta=\vartheta$, so the inverter model can be easily reduced to the linear equation:

$$P = \frac{\vartheta}{X_{filter}} \qquad (3\text{-}24)$$

Since the frequency of the power oscillation from the wave is rather low (values between 0.1 to 10 rad/s include all the possible range of operation), a PI inverter controller with K_P=0.1 and T_I=0.1s ensures that the inverter output P_{inv} exactly matches the reference value P_{ref}.
The DC bus is a simple integrator given by the time constant T due to the capacitance installed on the DC bus itself.
The actual value of the capacitance depends upon the size P_{dcr} of the PTO and the DC voltage V_{dcr} as:

$$C = T \frac{P_{dcr}}{V_{dcr}^2} \qquad (3\text{-}25)$$

Assuming a rated power of 200kW and a rated voltage of 1000V, capacitance values from 0.1 mF up to 10mF correspond to time constants ranging from 0.5ms up to 50ms.

3.2.2.2 DC Voltage regulation

In any case with a PI voltage regulator having K_P=100 and T_I=0.1s, the Bode diagram of the closed loop transfer function between the amplitude of the DC voltage and the input power P_{wave}, is reported in Figure 57 for different values of the time constant T (50ms red, 5ms blue, 0.5ms green).

In the interesting range of frequencies the gain of the closed loop function is -40dB, which means that the amplitude of the power fluctuation is reduced by a factor 1/100.

It means that even with a small capacitance a power fluctuation having an amplitude up to the rated value will never move the voltage on the DC bus more than 1%.

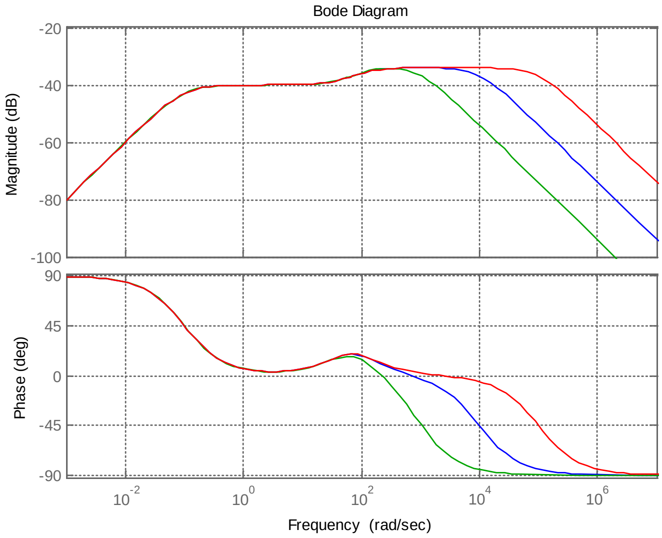


Figure 57. Bode plot of the closed loop transfer function between the input power and the DC voltage with fast PI voltage regulator.

This approach means that the power transferred to the grid has exactly the same fluctuation content of the source. This requires large compensation devices installed on the AC grid.

A different approach is that of increasing the amount of storage on the DC side (i.e. increasing the time constant of the capacitance in the model adopted) and slowing down the DC voltage regulator, to just follow the slow variations of the average value. It means reducing the proportional gain to 0 and leaving a slow integrating component. In the Bode diagram of Figure 57 we supposed to have a 1000s time constant on the integral component. The Bode diagram still represents the closed loop transfer function between the amplitude of the DC voltage and the input power P_{wave}, for different values of the time constant T (0.05s red, 0.5s green, 5s blue and 50s cyan). It’s clear that, in order to have voltage fluctuations below 10% starting from the frequency of 0.2rad/s, a rather large time constant is needed (some tens of seconds).

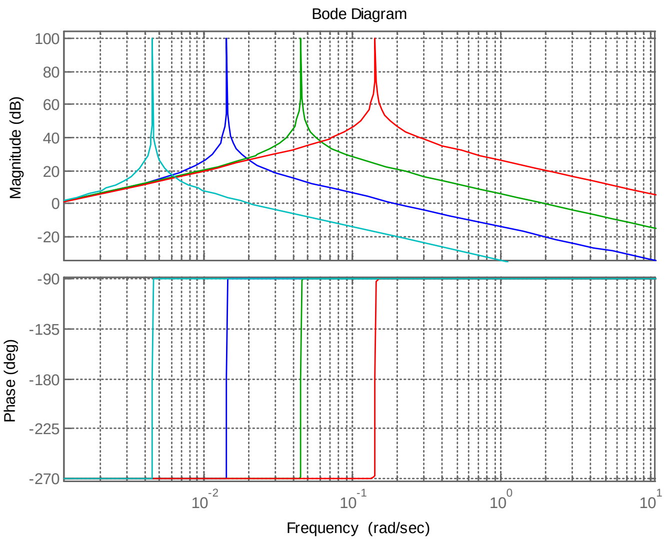


Figure 58.Bode plot of the closed loop transfer function between the input power and the DC voltage with a slow integrator voltage regulator.

It means that, with the same values of rated power and voltage, a supercapacitor having a rated capacity of 10F is needed. It is worth remarking that supercapacitors show a capacitive behaviour up to frequencies of few tenths of Hz. For higher frequencies, the resistive component becomes predominant with respect to the capacitive one.

3.2.2.3 *Simulation*

The two modes of operation have been tested on a Matlab model as shown in Figure 59 where the input power P_{wave} is composed by a constant value added to a continuously increasing oscillating components both having a unitary value.

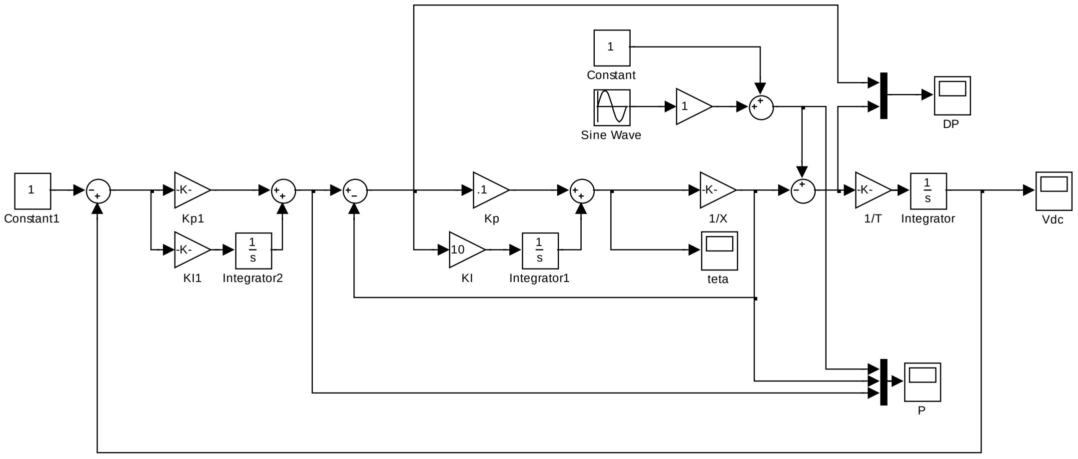


Figure 59. Scheme of the Matlab model.

Figure 60 shows the input power during the simulation with a frequency which ranges from 0.3 up to 2 rad/s (i.e. wave period from 21s down to 3.1s).

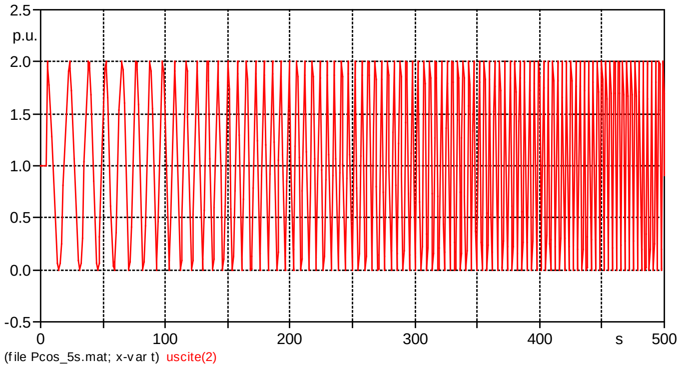


Figure 60. Input power from PTO.

Adopting a PI voltage regulator having K_P=100 and T_I=0.1s the voltage on the DC busbar is reported in Figure 61. It shows an oscillation with amplitude of 0.01p.u. that is consistent with the closed loop gain of -40dB appearing in the Bode plot for the considered frequency range. It is worth remarking that in the frequency range between 0.3 and 2 rad/s the gain of the closed loop transfer function remains constant at -40dB.

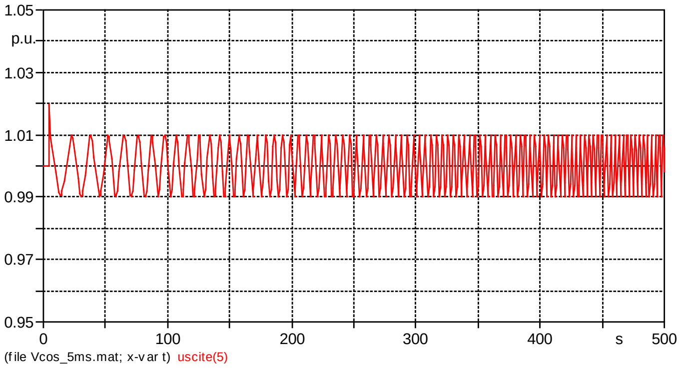


Figure 61. Voltage on the DC bus with constant voltage control.

If we suppose to adopt the different strategy of slowing down the voltage regulator (so that the request to the inverter power regulator only follows the slow changes in the mean values of the generated power but becomes insensitive to the oscillations at the wave frequency) the amplitude of voltage oscillation depends upon the time constant of the storage on the DC bus and on the frequency of the oscillation itself as also appears from the Bode plot in Figure 62. With a time constant of 5 *s* the amplitude of the voltage oscillation at ω=0.3rad/s is 60% of the rated value and decreases to 10% at ω=2rad/s. We must remark that with such large oscillations, the linearized model of the DC busbar has a questionable validity and actual voltage drop should be larger. In this case, the first negative oscillation would approach zero.

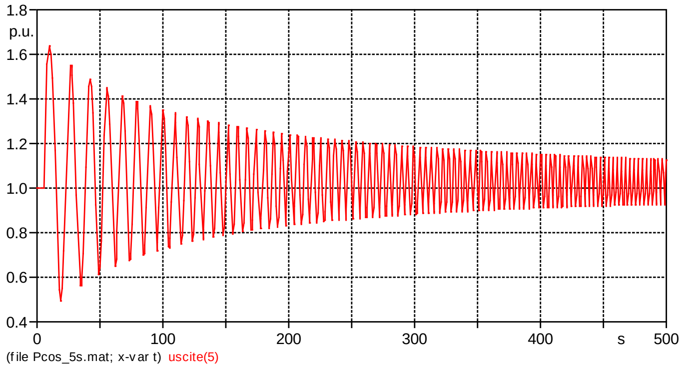


Figure 62. Voltage on the DC bus with slow voltage control (quasi-constant power output) with a DC time constant of 5 s.

By increasing the time constant up to 50s, the voltage oscillations are always below 6% and decrease to 1% for ω=2rad/s (see Figure 63).

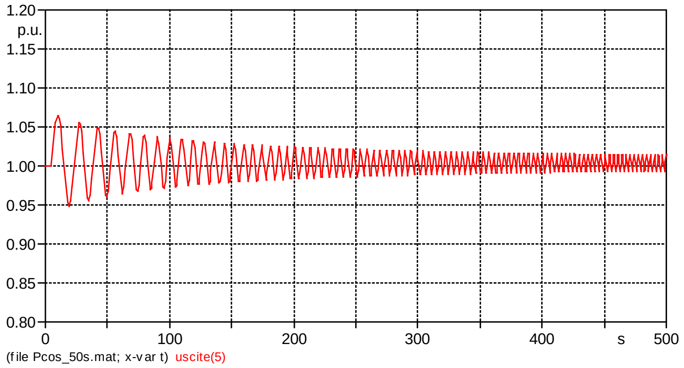


Figure 63. Voltage on the DC bus with slow voltage control (quasi-constant power output) with a DC time constant of 50s.

In both cases, the simulations refer to a power oscillation of 1p.u. with respect to the average value. If the oscillation can be confined to a lower share of the average value (thanks to a suitable arrangement of more PTOs), the results presented can be considered as the attenuation ratio of the voltage fluctuation with respect to power ones. To clarify, referring to the result with T=5s at ω=0.3rad/s, where an amplitude of 60% appears, we can consider that in case we get a residual power fluctuation having an amplitude of 20% of the rated power thank to the mutual compensation among the PTOs, the residual voltage fluctuation will be 12%, and will be reduced to 1.2% at the same frequency with T=50s.

3.2.2.4 Reactive power control

Whatever the active power control is, reactive power control in a fully controlled converter is completely decoupled (within the overall inverter capacity).

It is therefore possible either to choose among three basic control options. In all cases, we remark that, unless a large enough storage system is installed on the DC side (instead of the capacitance), a wave converter cannot supply a local load without the help of other devices with a controllable power output:

- Constant voltage amplitude operation: this mode of operation implies that all the reactive power regulation on the hub is performed by the wave converter. All the other possibly installed devices will always see perfectly constant voltage amplitude and will never participate into regulation. It is worth remarking that if other sources act in a similar operating mode on a system with very limited dimension (short electrical connections) reactive power sharing could be indeterminate and the operating point of each component would be outside the control of the management system.

- Constant reactive power output: in this case the inverter voltage amplitude is continuously controlled so that the reactive power output stays at a constant value (or to achieve a constant power factor). The device does not participate in fast voltage regulation that should be assured by other devices. The overall management system can arrange the reactive power set-point so to achieve a different sharing with the other sources.
- Voltage amplitude vs reactive power droop: in this mode of operation the amplitude of the voltage is continuously adapted to the actual reactive power output according to a static droop characteristic, as will be better described below for what concerns the storage system control. This operating mode enables the various sources to share the total reactive power demand according to their droop value and their actual size. All the sources thus participate in voltage regulation.

3.2.3 Storage system (SWVC) control

The system, in which different sources with different possible configurations supply a local load on an isolated operating mode, needs that the control system of the various sources can be properly operated in whatever condition.

First, we must remark that the renewable sources have usually a low degree of controllability, which implies that their output should be considered defined by the availability of the source. In fact, they can be hardly used for regulating the system. A storage system is in any case needed, not only for compensating the differences between the available power from sources and the load, but also for ensuring the needed voltage reference for the correct operation of all the converters which interface the sources with the local grid.

In many cases, renewable sources are connected through an electronic converter, whose final stage is an inverter. The inverter is controlled to inject into the grid the power produced by the source so that voltage on the DC stage remains almost constant (see above the description of the PTO converter control).

All these inverters need an external voltage reference to operate. When connected to a distribution grid, voltage reference is provided by the grid itself. When they operate on a stand-alone system, at least a voltage source is needed, which can be a synchronous generator or a voltage source inverter with some storage. This source should continuously adapt its output to the balance between the power from the sources and the demand from the load.

A completely different solution would be to connect all the sources to a DC bus where also a storage device is connected and use a single inverter (or a few inverters operating in parallel with a properly coordinated control) for supplying the load. Balance between the power injection from the sources and the demand from the load would be automatically supplied by the storage device.

Here, we consider a scheme where all the sources are directly connected to an AC system. In this case, the inverter which connects the storage to the grid must operate according to some specifications. Its characteristics will be:

- to operate only on the basis of locally available measurements,
- to be suitable for operating in parallel to the grid, in parallel to other similar devices or distributed generators as well as on a standalone system,
- it should not need to recognize whether the grid is connected or not.

These specifications might appear even too strict if we account the strong communication opportunities offered today for developing distribution management systems. A central control system might be conceived for on-line controlling all the devices installed in the grid. The inverter might therefore be coordinated with the other sources and operated in a master or slave configuration depending on the type and number of sources actually connected. This choice has the main drawback that a failure in the communication system or even a reduction of the bandwidth might cause the system failure.

The solution pursued here is to develop an autonomous system and exploit communication for the optimisation of the operating point. The system is therefore able to operate, within its capability, even without any communication being available.

To this purpose some remarks on the usual inverter control systems are reported.

3.2.3.1 Inverter control systems

Commercially available inverters can be roughly classified either as current controlled inverter or voltage controlled inverter. The first class is designed for operating in parallel to the mains and cannot supply a stand-alone system. Voltage controlled inverters can both operate in parallel to the mains (by usually defining the voltage amplitude and phase through a real and reactive power control loop) and on a stand-alone system (by working at constant terminal voltage and frequency). Anyway, a signal must be available for informing the controller about the operating condition. The parallel operation of an inverter to other sources and even to other inverters is today performed through a centralised control system.

To date, the sole control systems developed for enabling the parallel operation of many inverters without an on-line centralised controller, have been designed for large UPS systems. Frequently, these plants include different size UPS devices, often not installed all at once as well as not manufactured by the same company. All the other controllers for commercial inverters are designed according to the previously described classes, including the inverters used for connecting some kinds of generators (PV, fuel cells, some kind of wind turbines).

3.2.3.2 Droop control scheme

The control system which will manage the static compensator will be based on a droop scheme as described in Figure 64. It shows how the amplitude and phase of the inverter voltage are obtained according to real power vs. frequency and reactive power vs. voltage droop characteristics. Maximum power and maximum current loops are also included for limiting the device output within the capability of the components.

The response speed of these loops might be too low for protective functions after some events such as a fault on the grid. An inner and faster loop is therefore included for limiting the current peak at a compatible level.

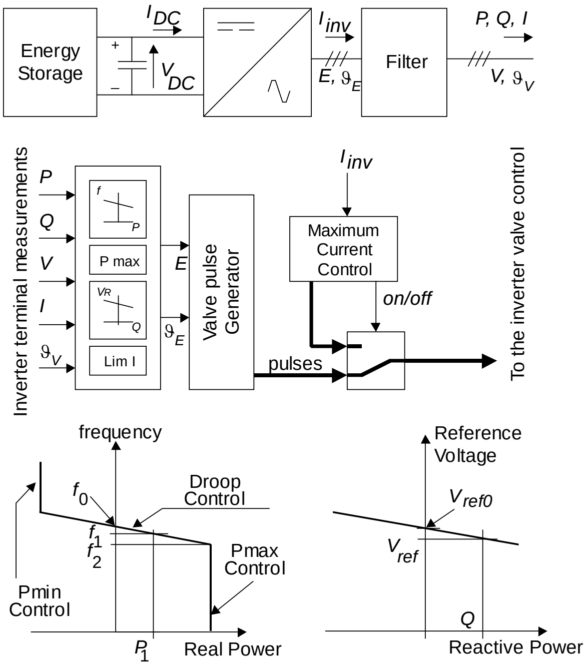


Figure 64. Principle control scheme.

When the inverter operates in parallel with the mains, the frequency is imposed by the mains itself. If the inverter frequency grows, its fundamental phase shift ϑ_E-ϑ_V with respect to the terminal voltage grows as well thus causing the power output to increase. The droop control system will then reduce the inverter frequency thus re-synchronising it with the mains.

On a stand-alone system, the frequency will be defined by the load; i.e. to power P_1 corresponds the frequency f_1 as shown in Figure 64.

If several inverters are connected in parallel to supply an isolated grid, they will share the load demand according to their droop characteristics, in the same way as large power plants subject to primary frequency regulation do.

A similar behaviour is obtained on the voltage amplitude side.

When the grid includes some other sources, this control strategy fits all the possible type of generators: synchronous, asynchronous and inverters. As the grid comes to a stand-alone configuration the system reaches a stable operating condition, although not optimised. No information is needed from the control centre, and the storage will deliver (within its capability constraints) the power needed for balancing the isolated grid.

The possibility of changing the value of f_0 or V_{rf0} on the two droop characteristics enables activating a kind of secondary control that operates within some cycles of the fundamental (200-300ms). The central controller for the optimisation of the operating point will define these reference values. The secondary control will then be also used for keeping frequency and voltage within quality standards.

3.2.4 System configuration and operating criteria

3.2.4.1 System layout

In the islanded system where two different renewable sources exist (wave converters and wind generators) to supply a local load, the minimum size of the storage system, in term of converter power, is the size of the load which need to be supplied in any case. Depending upon the size of the storage in term of energy, other sources should be integrated. If the overall energy produced throughout the year by the renewable sources is greater than the overall yearly consumption, a large enough storage could ensure that no further generators need to be installed. Energy simulations on a time scale of several years starting from recorded data on the availability of the sources are needed to show the actual size needed to be sure that the load is continuously supplied.

If the result is a too large storage volume or if, in any case, an alternative source is required for ensuring the possibility of supplying the load even in the case of a failure in the storage system or in the renewable source devices (so that the overall energy is reduced), a Diesel genset should be included among the generators.

Finally, in order to cope with the possibility to have surplus power even when the battery system is fully charged (according to the maximum level defined by regulation criteria), two options can be considered: either to install a dummy controllable load, which dissipates the surplus power, or to enable the possibility of reducing the power from the renewable sources.

The configuration that has been therefore considered, for covering all the possible cases includes:

- Wave generator
- Wind generator
- Diesel generator set
- Electrochemical Storage
- Dummy load

The system also includes the possible connection to an external grid to show that the control option adopted is also suitable for grid operating systems and is able to manage the islanding and paralleling transient.

3.2.4.2 Operation on the isolated system

As mentioned before, the renewable generators operate as uncontrolled power sources, where the power output depends upon the primary source.

Power fluctuations are transferred to the grid unless proper provisions have been undertaken, such as described in previous paragraphs. In any case only short terms fluctuations can be filtered by the generator converter system, while long term fluctuations are in any case reflected on the grid.

To ensure a proper operation in the various possible configurations and a suitable sharing of the balancing service, it is advisable that all the controllable resources (storage, Diesel and dummy load) are operated according to a frequency vs. power droop control scheme. It is, in any case, possible that only one of these sources regulates the frequency by adopting an integral controller with zero droop so that the other sources stay at a constant power. If a suitable droop remains on the other two sources, they can immediately participate in the regulation if the one with integral control reaches its maximum output.

Also for what concern voltage amplitude regulation by acting on the voltage amplitude, a similar voltage vs. reactive power droop control has been adopted. It is worth remarking that also the renewable sources can participate in voltage regulation by providing reactive power. Although a low voltage grid has mainly a resistive behaviour, reactive power exchange is determined by the voltage difference across the reactance of the filters of each interfacing inverter and the internal reactance of the synchronous generator.

Each of the sources is therefore controlled by an internal control loop which defines the overall system frequency and voltage according to the combination of the various droop characteristics, as it happens in the interconnected power systems by means of the primary regulation. The actual values depend upon the set-points adopted for each loop. In addition, the sharing among the sources depends upon these set-points (such as the values of f_0 or V_{rf0} in Figure 64). An external and central controller needs to be implemented which defines, according to general optimization criteria, the set-points to be used, similarly to what the secondary frequency regulation control does in the interconnected power system. In any case, even if not optimal set-points are defined or if set-points are not updated due to communication failure, the system operates correctly, within the capacity of each component.

3.2.5 System modeling

A comprehensive model has been developed in Matlab/Simulink framework with a sinusoidal approximation of the operation of the various converters. It is also available the possibility of adopting a PWM modelling, but simulation times would be unacceptable for the time scale of some seconds.

3.2.5.1 Purpose of the model and hypotheses

A Matlab/Simulink model of the system has been developed including the components listed above. The Simulink scheme is shown in Figure 65.

Figure 65. Scheme of the Matlab/Simulink model.

Fig. 1 Scheme of the Matlab/Simulink model

The scheme includes a central 690V AC busbar where the following components are connected: the wind generator (magenta), the wave generator (cyan), the Static Watt Var Compensator including the storage system (green), the grid with the paralleling switch (blue), the synchronous generator with its Diesel prime mover and voltage regulator (red), two constant loads modelled as parallel RL branches: Load 1 always connected and Load 2 switchable (yellow) and, finally, a controllable load with frequency/power droop control (yellow). The colours of the blocks correspond to the colours of the relevant curves in the on-line graphs representing real and reactive power.

When ending the simulation a .mat file (output.mat) is saved which includes several interesting variables for post processing. The saved data are:

- t=simulation time [s];
- Freq=system frequency [Hz];
- V_Grid=rms voltage at grid terminals [V];
- V_bus=rms voltage on the system busbar [V];
- V_batt=battery voltage [V];
- P_Wave=Active power from the wave converter [kW];
- P_Wind=Active power from the wind converter [kW];
- P_Sync=Active power from the synchronous generator [kW];
- P_Grid=Active power from the grid [kW];
- P_SWVC=Active power from the storage system [kW];
- P_Load=Active power to the sum of load 1 and 2 [kW];
- P_ContLd=Active power to the controllable load [kW];
- Q_Wave=Reactive power from the wave converter [kvar];
- Q_Wind=Reactive power from the wind converter [kvar];
- Q_Sync=Reactive power from the synchronous generator [kvar];
- Q_Grid=Reactive power from the grid [kvar];
- Q_SWVC=Reactive power from the storage system [kvar];
- Q_Load=Reactive power to the sum of load 1 and 2 [kvar];

The grid, the passive load 2, the wind generator, the wave converter and the Diesel generator can be connected or removed from the grid by acting on the relevant breaker (the grid breaker is a parallel breaker which also checks synchronization conditions before closing). The storage system, the controllable load and passive load 1 are always connected. To simulate cases where one of these components is not in service, just set to a very small value (not zero) its rated power.

3.2.5.2 Model description

3.2.5.2.1 SWVC

The inverter interfacing the storage system is modelled as voltage source inverter where the phase and the amplitude of the fundamental voltage can be controlled to perform different possible functions.

The inverter bridge is not modelled and it has been replaced with three voltage generators which directly output the voltage at inverter terminals. It is possible either to use a sinusoidal equivalent model (which speeds up the simulation without loosing accuracy for the dynamics under study) or adopting the full PWM model which needs very short time-step for simulation and long calculation time. The model includes the inverter AC filter whose parameters are defined in the block mask. A flag in the block mask enables choosing between the sinusoidal equivalent model and the full PWM one.

Concerning regulation, it includes the two droop control loops described in Figure 64. It is also possible (through the external input Dr/fc) to choose between the frequency vs power droop control and a constant frequency one. The latter can be adopted when the system operates isolated from any external grid, so that the storage system defines the frequency but will be the only source to regulate; all the other regulating devices (Diesel and controllable load) will always see a constant frequency value so will never change their output. It's worth remarking that a constant frequency operation is never compatible with the possibility to operate in parallel with the grid.

In the case of the SWVC, a constant reactive power control is not implemented, since it would not be compatible with the balancing service the SWVC is installed for. Also a constant voltage amplitude control is not implemented since the SWVC would be charged of all the regulation service and reactive power would not be shared with the other sources.

The parameters of the system and of the regulation loops are defined in the mask. The reference values V_0 and f_0 (which define the operating voltage and frequency at zero real and reactive power) are external input, since it can be adjusted if a different sharing among the sources is needed.

Figure 66 shows the main control loops which define the amplitude and phase of the fundamental voltage of the inverter. Their structure is presented below in Figure 69 and Figure 71. The magenta inverter block contains the inverter itself and the blocks which, starting from the desired amplitude and phase define the actual waveform.

•

Figure 66. SWVC main control loop block diagram.

The details of the inverter block are shown in Figure 67. The block Eabc1 combines the amplitude and phase values to achieve the actual instantaneous value of the desired voltage on the three phases of the inverter bridge. If, in the outer mask, it has been decided to develop a full model of the PWM strategy, the block PWM is active and the output is the sequence of impulses between the ±Vdc levels.

Figure 67. SWVC internal control.

The electrical part of the inverter model is shown in Figure 68. The three generators Va, Vb and Vc output the three instantaneous voltages defined in the vector Eabc mentioned above. There are two measurement blocks for voltage and current evaluation at both terminals of the filter which in also included in this block.

Figure 68. Scheme of the electrical part of the SWVC model.

Figure 69 shows the logical scheme of the phase controller. Depending upon the Set value defined inside the block Switch f_P, the upper or the lower path is active. The lower is usually active in normal operation: the function f(u) represents the droop function so that the desired frequency value in p.u. is calculated as $f_r = f_0 - droop \cdot P$ .This value multiplied by $2\pi f_{\mathrm{nom}}$, is then integrated in the Int block to achieve the voltage phase. If the DR/fc flag is set on 0, meaning that a costant frequency operation is desired, the droop effect is by-passed and $f_r = f_0$.

The Set value defines whether the system operates in normal mode or in power limiting mode which is activated in case the power output reaches the maximum or minimum power. In this case the maximum or minimum power becomes the power reference Pref and the PI controller defines the inverter voltage phase shift with respect to grid so to achieve this power. The output of the PI controlled is summed to the grid voltage phase to get the absolute phase of the inverter voltage. When switching from one operating condition to the other, the frequency integrator or the integrator within the PI controller which becomes active after switching is reset to a value that ensures that no phase jumps happen.

We remark that, in power limiting operating mode, the inverter is able to correctly operate only if an external source defines the voltage reference and balances generation and demand. If the inverter operates on a passive grid, system frequency will start to increase or decrease depending on whether it is operating at the minimum or maximum power limit.

Figure 69. SWVC voltage phase control system.

The algorithm for defining whether the inverter has to operate in normal mode or in power limiting mode is reported in Figure 70. The passage from normal operation to power limiting (Set passes from 0 to 1) mode happens when the power output overcomes the maximum (upper flip-flop block) or minimum (lower flip-flop block) values (usually 1 and -1 p.u.) by 2%. The maximum or minimum threshold becomes the power reference for the PI controller of Figure 69.

Reset to normal operation (set passes from 1 to 0) happens when, while operating in power limiting mode, the frequency overcomes the value corresponding to the knee of the regulating droop curve or when, in any case, power goes below 40% of the maximum power. These conditions are valid with opposite signs for the minimum power threshold.

Figure 70. SWVC power limiting control switching logic.

Voltage amplitude regulation is described in Figure 71. In normal operation the lower branch is active while the upper one is activated when the inverter operates in current limiting mode. To avoid step changes in the voltage amplitude, the same PI controller is active in both cases while a different regulator input signal is selected through the switch operated by the Set_VI control variable.

The block f(u) implements the droop function $V_{ref} = V_0 - droop \cdot Q$ which defines the voltage reference according to the droop control strategy. This value is compared to the terminal voltage and the resulting error (corrected by an adjusting multiplying factor) is sent to the controller.

When reaching the maximum admissible operating current Imax, the difference between maximum current and actual current values becomes the input to the regulator so that the inverter starts operating in a constant current mode. The sign of the error depends upon the sign of the reactive power exchanged. In fact, if reactive power is positive (injected into the grid), voltage reduction results in current reduction, while, if reactive power is negative (absorbed from the grid), voltage reduction results in current increase. When operating in current limiting mode, the voltage at inverter terminals will be lower than the reference value (if Q>0) or higher (if Q<0). If no other sources contribute to voltage regulation, voltage will move until the demand from the load will be compatible with the current limit or will collapse if the load is not voltage sensitive.

The block Switch V_I, detailed in Figure 72, defines the criteria for switching from one operating mode to the other and vice versa.

Switching to maximum current control is activated as the current overcomes the threshold defined in the external mask of the SWVC (e.g. 1.5 p.u.). Rest to normal operation happens when voltage goes back above reference value (if Q>0) or below reference value (if Q<0). A 2% threshold is adopted to avoid repetitive set and reset switchings.

Figure 71. SWVC voltage amplitude control system.

Figure 72. SWVC maximum control switching logic.

3.2.5.2.2 Wind and wave converters

Wind and wave converter are both modelled as a voltage source inverter where the phase of the fundamental voltage is controlled so to inject the power profile specified inside the blocks P_wave and P_wind into the busbar. As described in previous paragraphs, the wave system inverter is controlled either to keep the voltage on the DC bus at a constant level (thus transferring all the power fluctuations to the grid) or to smooth the source fluctuation while following the average power value. In both cases the power the inverter supplies is defined by this control logic and can not be subject to other requirements. Also the wind system inverter has the same control scheme and the power from the wind, although less fluctuating in the short term, is directly injected in the grid. The mentioned blocks can be replaced with whatever profiles. For showing the model operation, the wave power profile is composed by an average value with a sinusoidal fluctuating component with a period of 2 s. The wind power profile is a ramp from an initial value to a final one.

As for the SWVC model, the inverter bridge is not modelled and it is possible either to use a sinusoidal equivalent model or adopting the full PWM model through a flag in the block mask. The model includes the inverter AC filter whose parameters are defined in the block mask.

Phase control is reduced to simply a power regulator (Figure 73) which choose the right phase value so that the power injected into the grid matches the reference value either it is a constant or a variable value. It operates as the upper part of the scheme of Figure 69 of the SWVC regulator which is active when it runs at maximum or minimum power instead on normal droop regulation.

Figure 73. Inverter voltage phase control system

Concerning voltage amplitude control the model includes two possible options. The first is to operate at constant (or in any case defined) reactive power value. In this case the inverter terminal voltage amplitude is controlled so to achieve the desired reactive power (even zero). In this case the input Qref (Qr_wind and Qr_wave) defines the desired value (the input V_0 is inactive). The second is to adopt a voltage droop control as described in Figure 64. In this case the input V_0 defines the voltage level which corresponds to zero reactive power in the graph of Figure 64 (the input Qref is inactive). A flag in the block mask enables choosing between the two possibilities. The regulating scheme is the same of the SWVC with an additional input to the PI regulator.

3.2.5.2.3 Diesel generator

Diesel generator is modelled using the standard synchronous model available in the libraries of Matlab/Simulink. For the purpose of this study a diesel prime mover can be simply modelled, as shown in Figure 74, as afirst order dynamic system (the integrator with feedback) having a time constant of few hundreds of milliseconds. A static characteristic with a power vs frequency droop is implemented. The droop value (which is the gain Gov in the figure) can be set in the block mask while the value P0, which corresponds to the power at rated frequency, is an external input as it can be adjusted if needed.

Figure 74. Diesel generator governor model

Voltage regulation is modelled through a standard static exciter having a transfer function given by:

$$G(s) = \mu_0 \frac{1 + sT_1}{1 + sT_2}$$

The scheme is reported in Figure 75. Voltage reference is not kept constant as it would imply that only the Diesel generator performs reactive power regulation. Voltage reference is thus adapted to reactive power output according to a droop characteristic, so that the value to be compared with the voltage V measured at generator terminals is $V_{ref} = V_0 - droop \cdot Q$. The parameters of the exciter and the droop value can be set in the block mask, while the value of V0 is an external input.

Figure 75. Diesel generator AVR model with voltage droop.

3.2.5.2.4 Controllable load

The controllable load model is made of three current generators whose current value is calculated as the product between a variable admittance value and the terminal voltage. Its scheme is reported in Figure 76. The upper part includes the three current generators on the right whose amplitude is the product between the terminal phase voltage measured through the three voltage meter blocks and the admittance calculated in the lower part of the scheme.

The admittance is calculated, in per unit values, as:

$Y = \frac{f_0 - f}{droop}$ limited in the range between 0 and 1

When f is greater than f_0, the admittance is null, while it increases as the frequency falls below f_0. The maximum power (Y=1) is achieved when $f=f_0\text{-}droop$. A first order block with a time constant of 50ms is added to avoid power oscillations with low droop values.

This model represents the behaviour of a passive load connected through a fully controlled converter which modulates the absorbed power.

The load is supposed to behave as a purely resistive load, so reactive power is always zero.

Figure 76. Controllable load model.

3.2.5.3 Result presentation

During simulation the graphs shown in Figure 77 are available as default configuration. More graphs are available inside the various blocks and can be open if necessary. Singular power graphs as well as voltage and current amplitude graphs at each component terminals are gathered inside the “Power scopes” block detailed in Figure 79. Many other graphs are available in the blocks describing each component as it can be noted in all the schemes presented in the previous paragraphs.

The first two graphs respectively show the active and reactive power exchanged by each of the component. The colour of each curve corresponds to the relevant block in the scheme of Figure 65. Two yellow curves represent the power of the passive load (sum of load 1 and 2) and the controllable load.

The other two graphs show the system frequency and the voltage on the system busbar, which corresponds to the voltage at SWVC terminals since it is always connected.

As already mentioned, these variables are also saved in a .mat file. These values have then been post-processed to present the results in the next paragraph in a clear fashion.

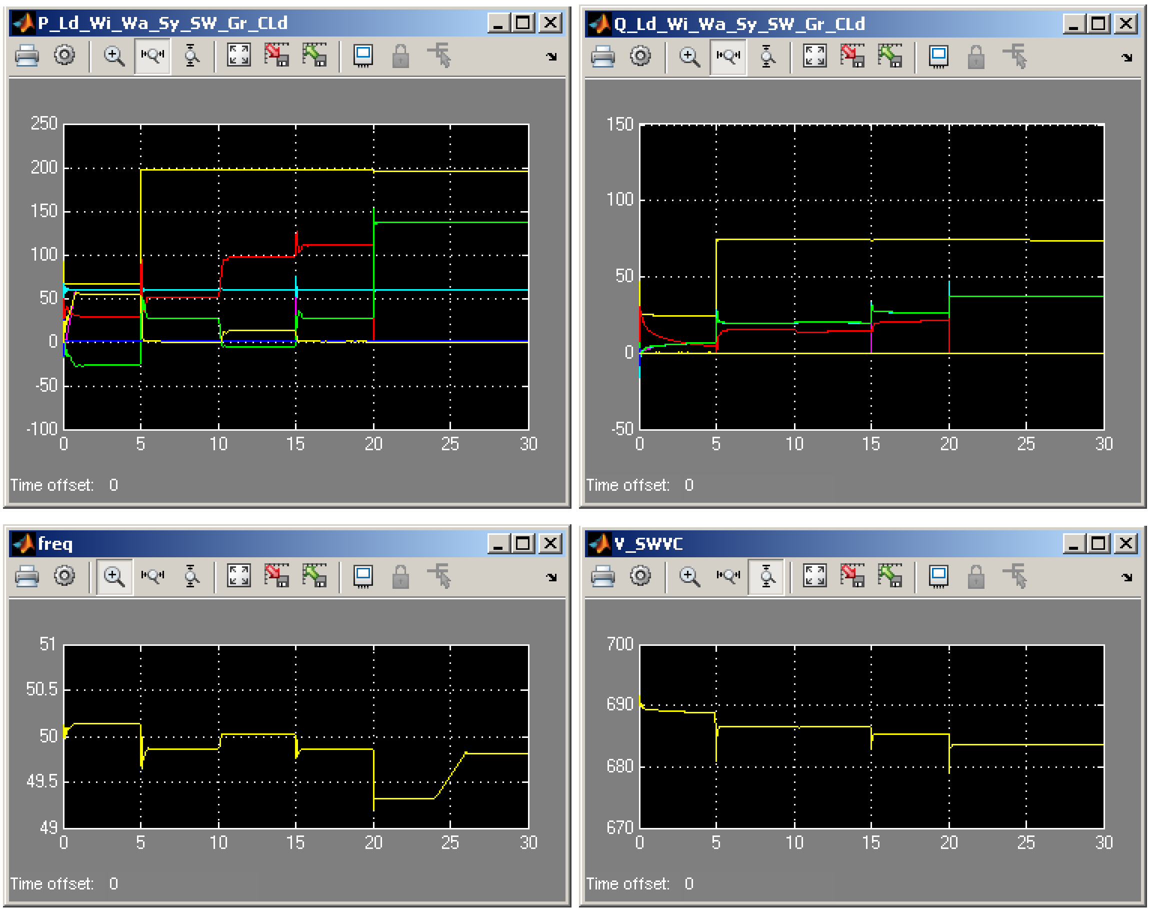


Figure 77. Graphs shown during simulation with smoothed wave generator output

Figure 78. Block with the main scopes for result monitoring

3.2.6 Simulation examples

A simulation which includes several events has been used to describe the system operation and show the feasibility of a solution with a storage system having the same power of the total load.
The size of the components adopted for the simulation is:

- Wind generator: 200kW
- Wave converter: 200kW
- Load 1: 66.7kW, 25kvar
- Load 2: 133.3kW, 50kvar
- Diesel generator: 200kW
- Controllable load: 100kW
- SWVC: 200kW
- The grid is supposed to be always disconnected.

The initial system configuration is:

- Load 1: connected
- Load 2: disconnected
- Wave converter: operating at P=60kW
  voltage droop control operating with V_0=1p.u. and 5% droop
- Wind generator: operating with P=0kW
  voltage droop control operating with V_0=1p.u. and 5% droop
- Diesel generator: operating with frequency droop control with P_m=0.2p.u. 5% droop

and voltage droop control with V_0=1p.u. and 5% droop

- SWVC: operating with frequency droop control with f_0=1p.u. and 2% droop and voltage droop control with V_0=1p.u. and 5% droop
- Controlled load: operating with frequency droop control with 1% droop

The events simulated during a 30s simulation are:

- 1 t=0-1s: wind generator ramp up to 60kW in 1s
- 2 t=5s: connection of passive load 2: 133.3kW and 50kvar
- 3 t=10s: step of Diesel governor reference Pm from 0.2p.u. to 0.5p.u.
- 4 t=15s: Wind generator trip
- 5 t=20s: Diesel generator trip
- 6 t=24-26s: ramp of SWVC set-point f_0 from 1p.u. to 1.01p.u.

Events 1, 2, 4 and 5 are some of the possible events that can happen during the operation of the system. The events 3 and 6 are examples of possible corrective actions that the central control system should take to keep the system operating point near the rated values and to achieve a good dispatching of the controllable sources.

The same transient has been simulated with two possible operating options for the wave converter. First, it has been supposed that a large enough capacitor has been installed on the DC bus so the power output appears to be constant at the average value of 60kW. Then the simulation has been repeated supposing to have a 40kW oscillation with a period of 2s.

3.2.6.1 Simulation with smoothed wave power output

During the simulation, the results are presented as shown in Figure 79

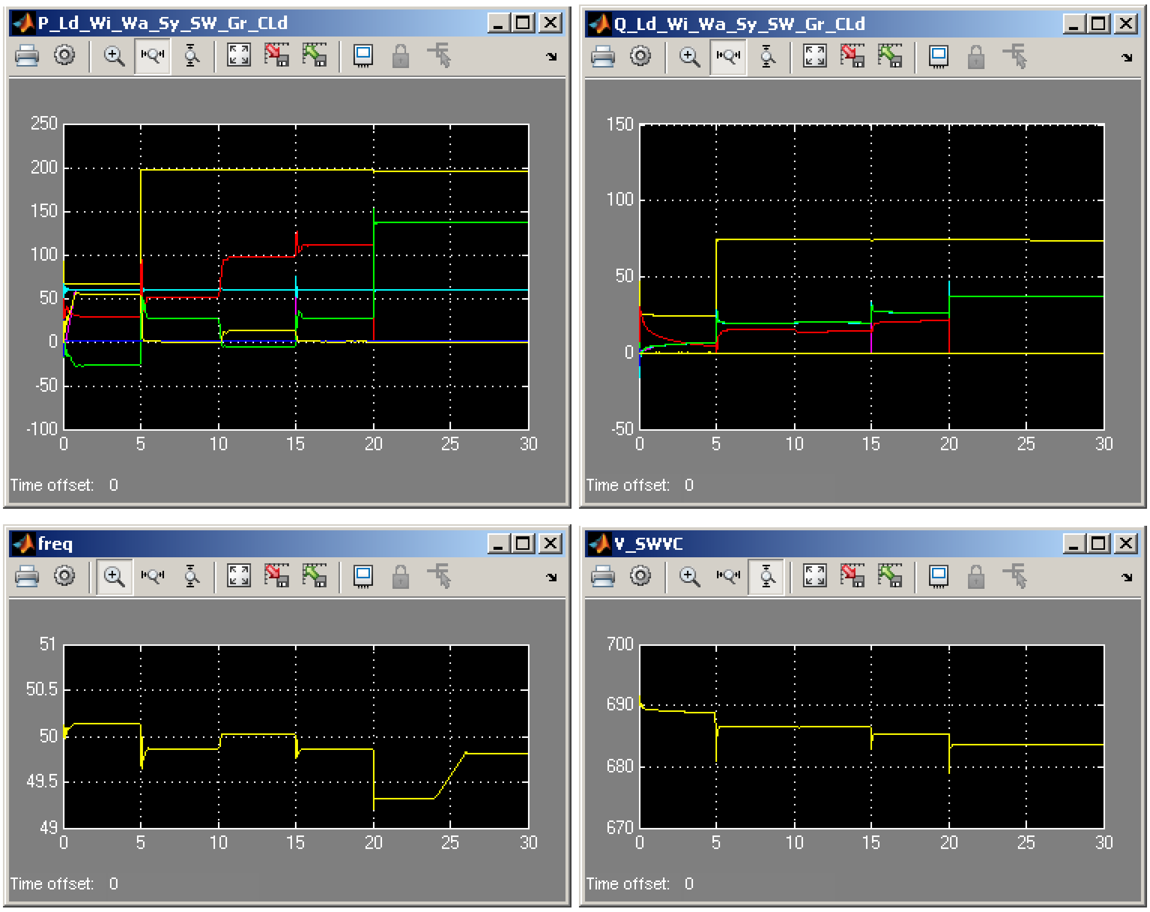


Figure 79. Graphs shown during simulation with smoothed wave generator output.

Below, results have been post processed for getting a clearer view. So, Figure 80 shows the real power exchanged by each of the components assuming that power from active sources are positive when injected into the grid (battery charging means negative power), while load power is positive when absorbed. All the graphs are presented with the same scale in order to ease the comparison among the various contributions. The sum of the power values from active sources should be equal to the sum of the total load demand (included the controllable load). The system losses are disregarded. In Figure 81 all the power curves are reported together to give a comprehensive view of power sharing. The system frequency is reported in Figure 82.

With the same sign reference Figure 83 and Figure 84 present reactive power values and Figure 85 the system voltage.

The initial load is only 66.7kW, which is covered by the wave generator (operating at 60kW) and by a small contribution of the Diesel generator. When the wind generator is supposed to ramp up to 60kW (from 0 to 1s), generation from renewable sources overcomes the demand from the load. The frequency increases and the Diesel generator, although having a set-point of 0.2 p.u. (40kW) decreases its output to 29kW according to its droop characteristic. Since the sum of generation (60+60+29=149kW) is still above the demand, both the storage system and the controllable load start absorbing power. The controllable load drains 55kW while the batteries are charged with 28kW. The frequency is at 50.14Hz as it results from the combination of the droop characteristics of the regulating devices (Diesel, Storage and controllable load, see Figure 82).

At t=5s the sudden load increase (133.3kW) is covered by reducing to zero the demand from the controllable load (55kW), by increasing the Diesel output up to 51kW (+22kW) and by the reversal of the flow from the storage system which passes from -28kW to 27kW (thus contributing with 55kW). The system frequency stabilizes at 49.86Hz.

To avoid discharging the batteries, it is supposed to increase the Diesel power set-point to 0.5p.u. at t=10s. Its output increases to 97kW, while the batteries begins to charge again at 6kW. The frequency goes slightly above 50Hz and the Controllable load balances the system with 13kW. It’s worth remarking that a different choice of the f_0 set-point for the various droop characteristics implies that a different sharing of active power would be achieved. Also the power increase from the Diesel generator is achieved by increasing its P_0 value, which moves its regulator droop curve.

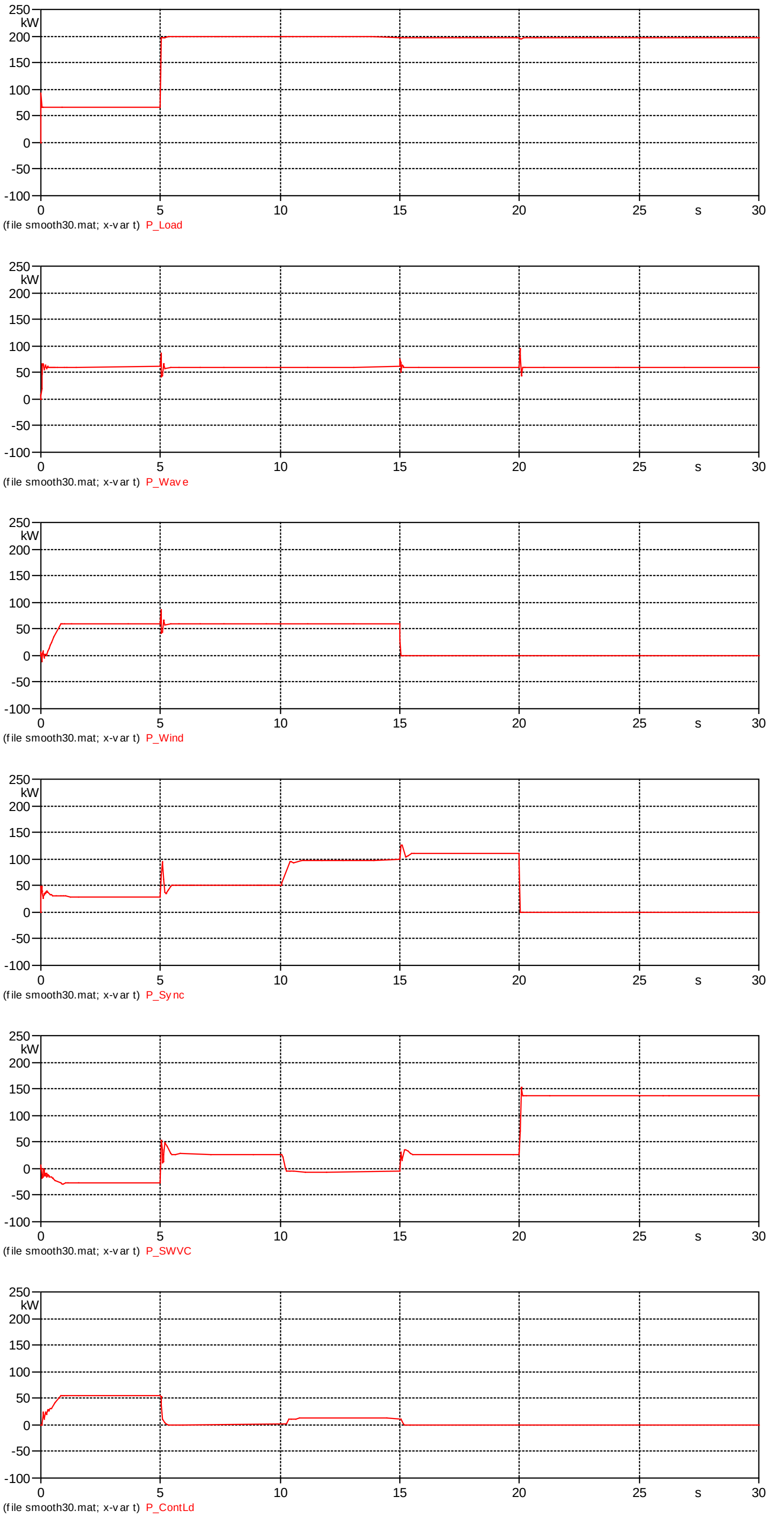


Figure 80. Real power. From top: Load demand, Wave generation, Wind generation, Diesel generation, SWVC generation, Controllable load demand

The following loss (t=15) of the wind generator, is covered partly by the Diesel generator and partly by the storage system, still according to their droop settings. Also the controllable load partly contributes by cutting to zero its demand.

To test the dynamic response of the storage system in the worse condition, at t=20s the loss of the Diesel generator is simulated. As a matter of fact the storage system remains the sole regulating device. The contribution from the wave generator reduces the unbalance but does not give any help for regulation. The frequency goes to 49.3Hz. Finally, the reference of the droop regulator of the storage system is increased (in the time interval from 24s to 26s), to move the system frequency closer to 50Hz (it reaches 49.8Hz). During this final transient, the power output from the storage system does not change as the load to be supplied remains the same. It simply changes the operating frequency as it is the only regulating devices still connected.

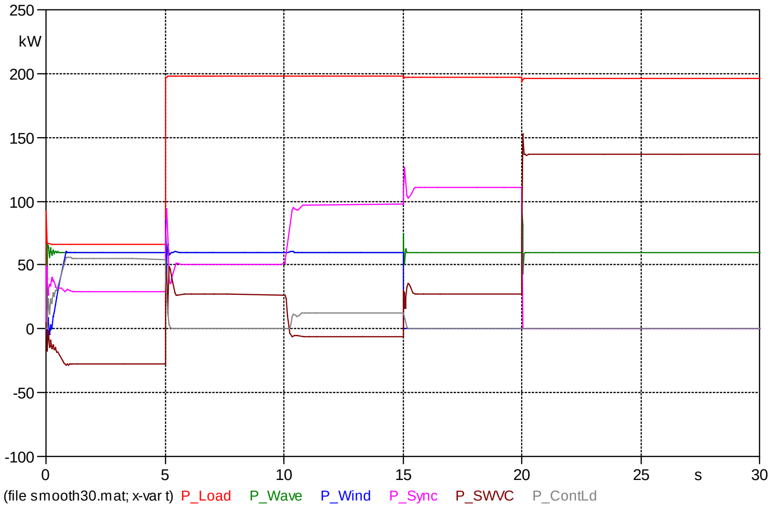


Figure 81. Comprehensive representation of all real power flows.

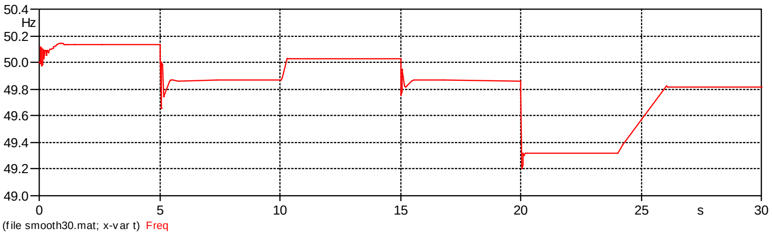


Figure 82. System frequency.

A similar behaviour can be observed for what concerns reactive power and voltage regulation. In this case, all the devices participate in regulating the reactive power. In fact, any inverter can be controlled to exchange the desired value of reactive power independently on the real power (within the total inverter capacity). At t=10s, when the Diesel generator increases its power output, no substantial changes in reactive power flows are observed.

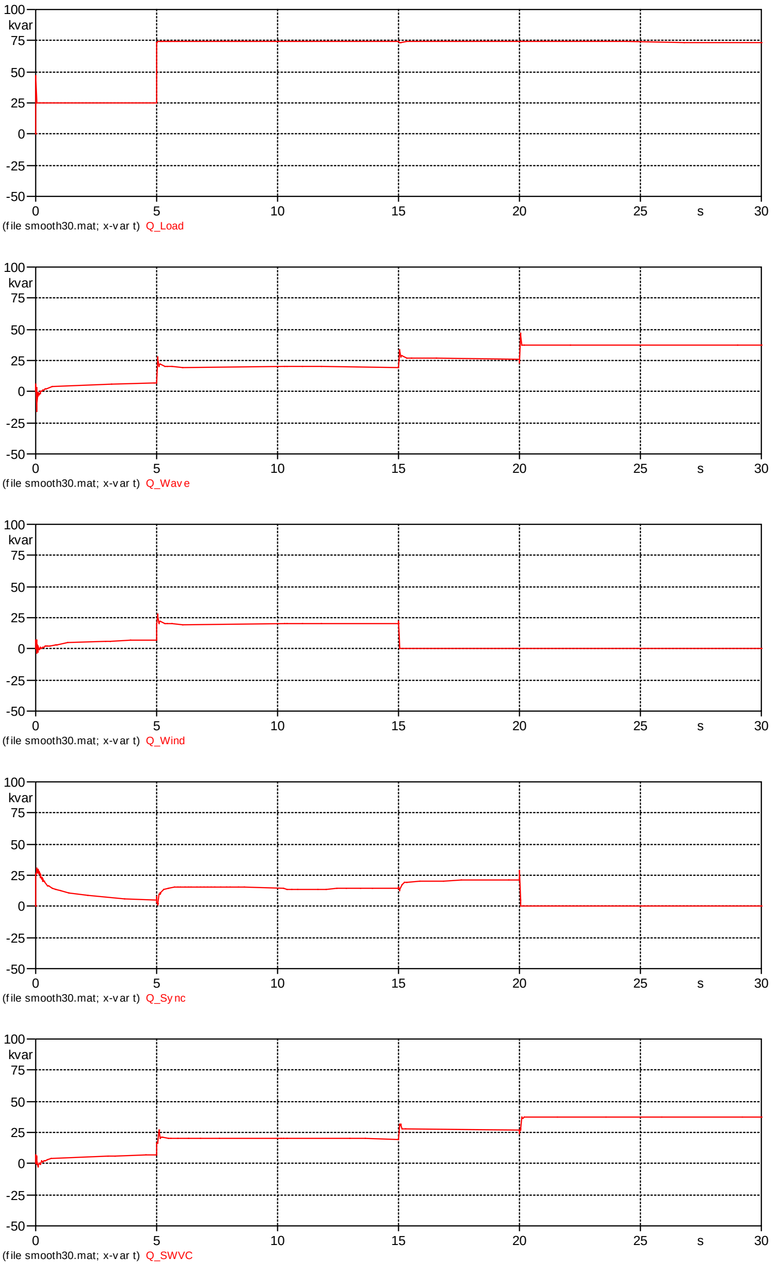


Figure 83. Reactive power. From top: Load demand, Wave generation, Wind generation, Diesel generation, SWVC generation.

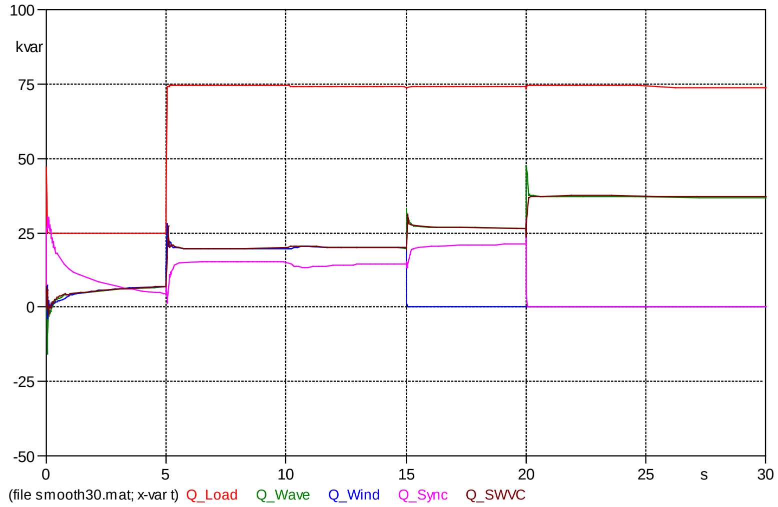


Figure 84. Comprehensive representation of all reactive power flows.

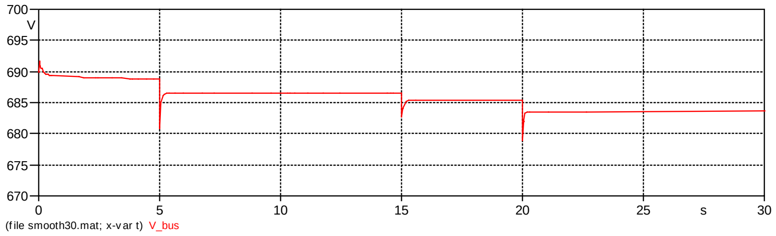


Figure 85. System voltage.

3.2.6.2 Simulation with fluctuating wave power output

The same sequence of events has been simulated also supposing that the power output from the wave converter is fully affected by the natural fluctuation of the natural source.

During the simulation the results are presented as shown in Figure 86.

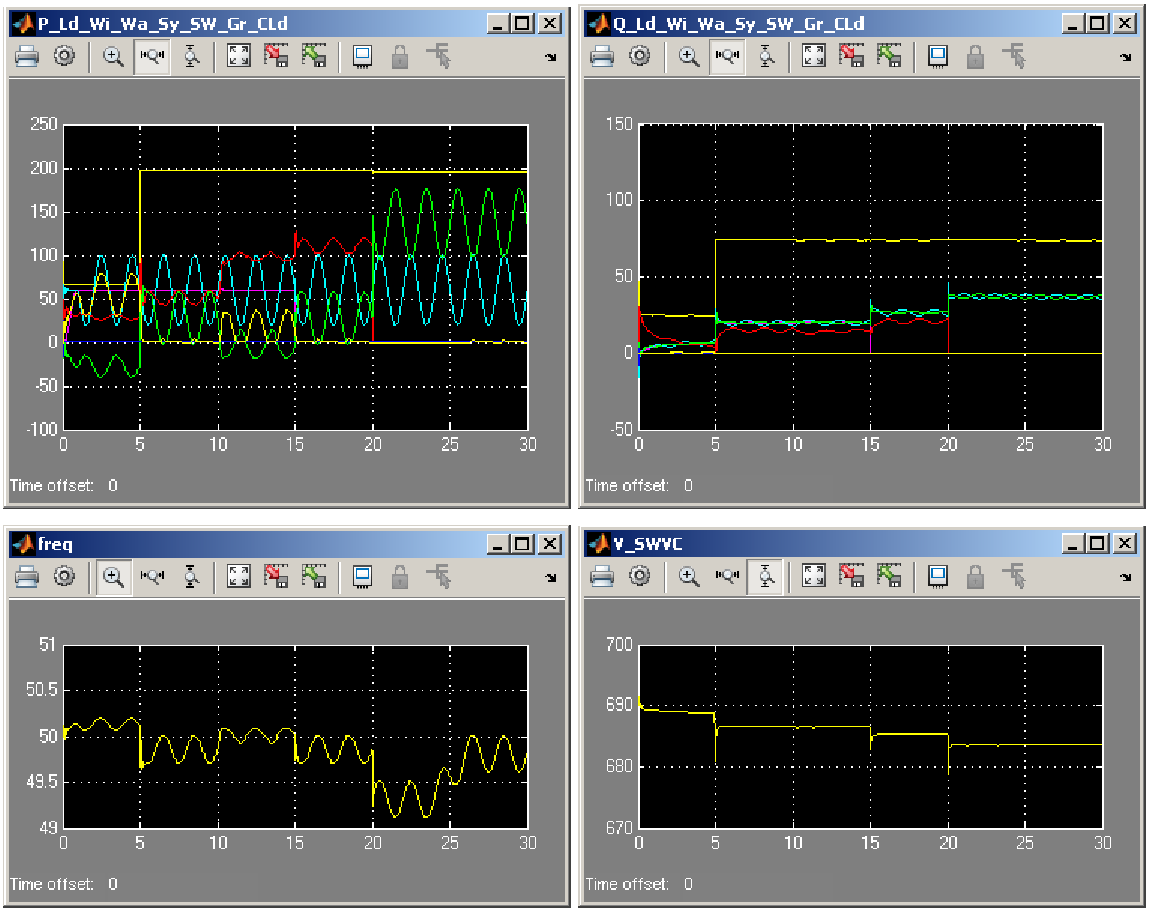


Figure 86. Graphs shown during simulation with oscillating wave generator output.

As for the previous case, results have been post processed for getting a clearer view. So, Figure 87 and Figure 88 report the real power of each device with the same reference as before, Figure 89 shows the system frequency, Figure 90 and Figure 91 report reactive power, and Figure 92 the system voltage.

As a consequence of choosing a frequency droop control, the system frequency fluctuates. As already mentioned, it would be possible even to impose a fix frequency value by making the storage system inverter operate as a constant frequency source. It would make power sharing very complex and stiff communication requirements should be imposed.

The average value during each 5s interval of the power supplied by each device is the same as the simulation before. The output from the Diesel generator, the storage system and the controllable load fluctuate to compensate the fluctuations of the wave source.

Diesel generator gives a small contribution since it has a larger droop (5%) compared to the storage system (2%) and the controllable load (1%).

When the average value of the frequency stays above 50Hz (in the intervals from 0 to 5s and from 10 to 15s), the controllable load gives a strong contribution and frequency fluctuation is reduced to less than 0.2Hz, while in the other intervals is 0.3Hz when the Diesel gives its contribution and 0.4Hz when only the storage system regulates (after t=20s)

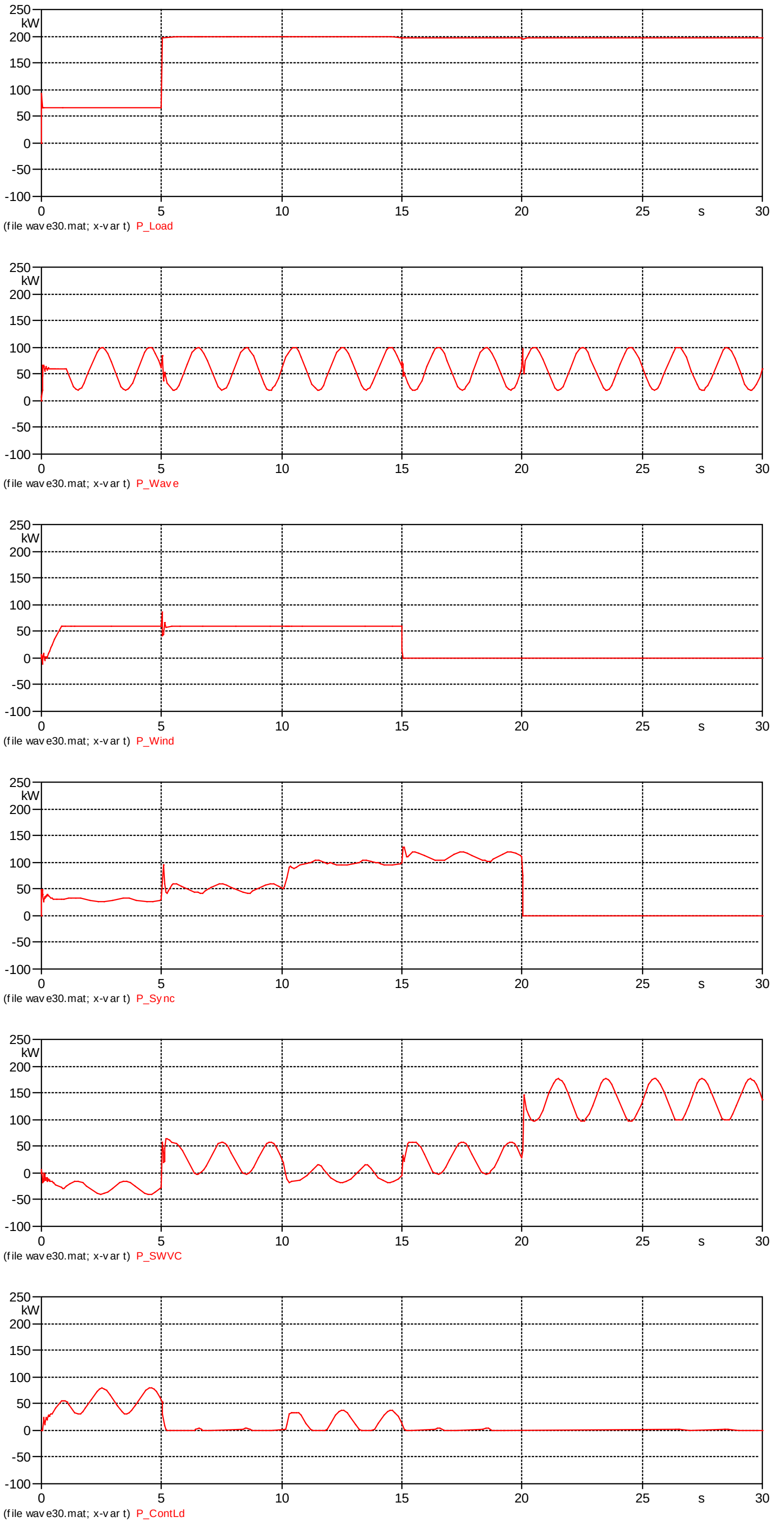


Figure 87. Real power. From top: Load demand, Wave generation, Wind generation, Diesel generation, SWVC generation, Controllable load demand.

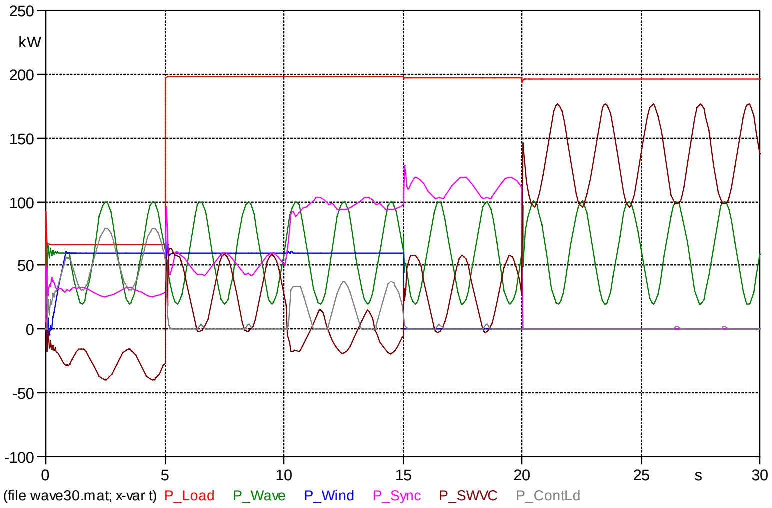


Figure 88. Comprehensive representation of all real power flows.

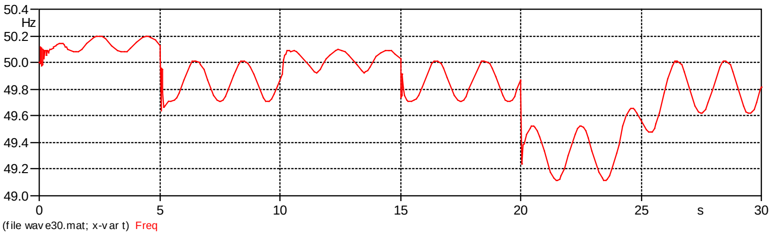


Figure 89. System frequency.

Some fluctuation also appears in the reactive power graphs as a consequence of the fluctuating active power flow across the wave converter filters.

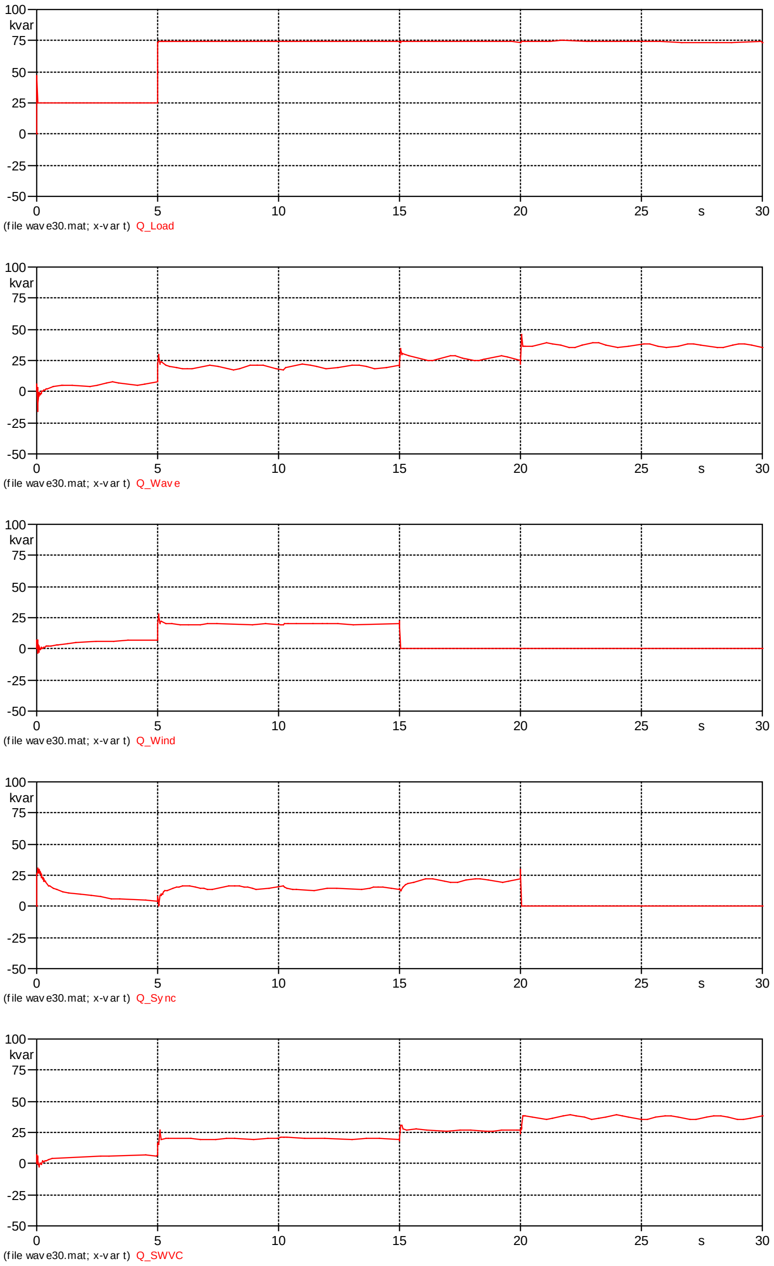


Figure 90. Reactive power. From top: Load demand, Wave generation, Wind generation, Diesel generation, SWVC generation.

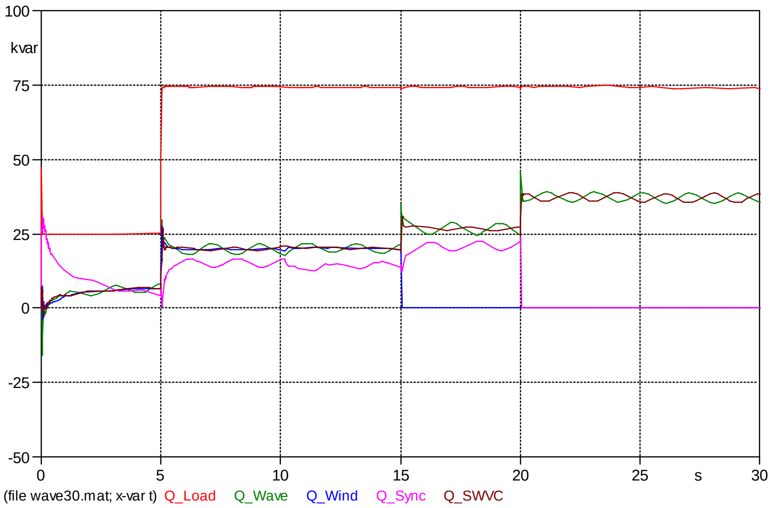


Figure 91. Comprehensive representation of all reactive power flows.

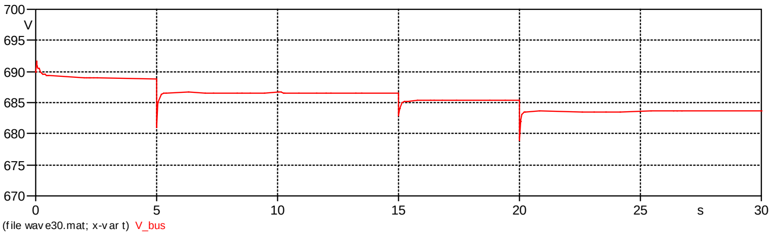


Figure 92. System voltage.

3.2.6.3 *Comparison*

Figure 93 compares the power output from the wave converter in the two simulations, which have the same mean value. Figure 94compares the response of the storage system and highlights the amplitude of the power oscillations, which are minimal when the controllable load contributes to regulation as shown in Figure 95. Finally, Figure 96 compares the system frequency.

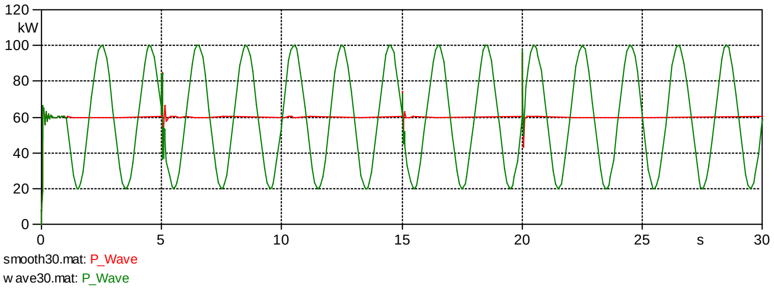


Figure 93. Power from wave converter.

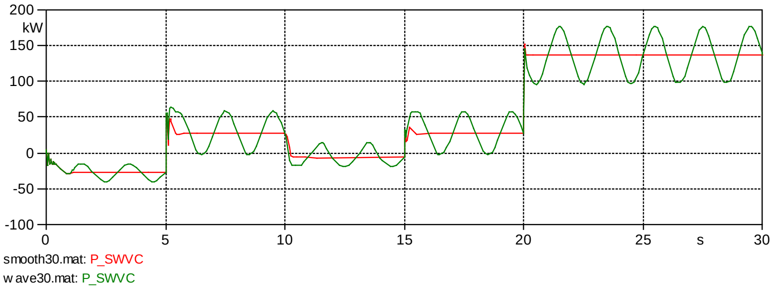


Figure 94. Power exchanged by the storage system.

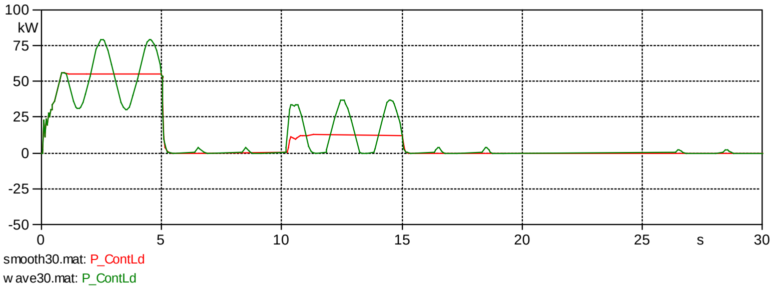


Figure 95. Power to the controllable load.

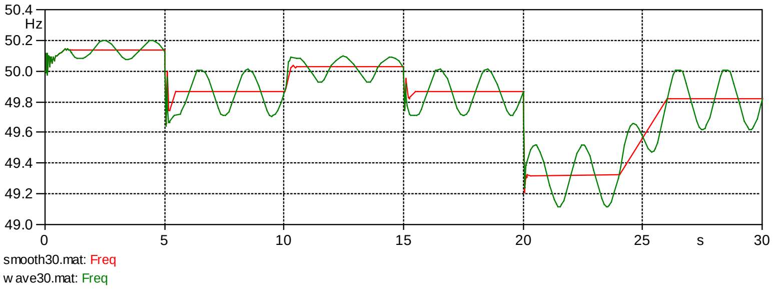


Figure 96. System frequency.

3.3 Electrical Modeling of offshore platforms: steady-state aspects

The model developed to study stationary aspects relevant to offshore platforms is finalized to analyse the behaviour of stand-alone or grid connected offshore hubs, in order to reproduce the global energetic balance generated by the presence of:
a) Renewable energy (RE) generators, e.g. Wave Energy Converters (WEC), Wind Turbine Generators (WTG), Photovoltaic systems (PV);
b) Emergency system, e.g. Gen Set (GS) with gas, gasoline, diesel, hydrogen or mixed fuel engine;
c) Storage systems: Battery, Hydrogen;
d) Dynamic loads e.g. fish farms feeding systems, maritime transport;
e) Possible grid connection.

The model takes as input the primary resources times series (e.g. wind speed and direction, wave direction and significant height/period), with a detail of three hours, and analyses different possible hub configurations in order to select the one correspondent to the maximum utilization of renewable resources in a reference time horizon. The choice of the three hours is related to the availability of resource data at three hour intervals at the moment of model definition, but the implemented equations are very general therefore the model is able to run even with other time resolution with minor modifications.

The analysis of the energetic behaviour of the platform in terms of time series is very important since storage systems sizing and the assessment of Gen Set fuel consumption can be done only throughout the evaluation (frequency and duration) of low energetic windows (wave and wind resources).

Each possible configuration can be declined in terms of:

- type, number, orientation, nominal power of renewable energy generators;
- type and size and operative parameters of storage systems;
- power and energy consumptions in term of time profile.

When simulating a stand-alone platform, according to the specific configuration under study the tool reproduces the energetic behaviour of each device considering the entire hub by means of its "bus-bar equivalent" in order to assure the global energy balance, hence acting as a sort of Hub Management System in which the Gen Set has to operate only if renewable generators and storage systems are not able to feed the local loads.

The developed model, although simple, is very general and offers the possibility to introduce a huge variety of generation/load/storage devices in order to create hubs of increasing complexity.

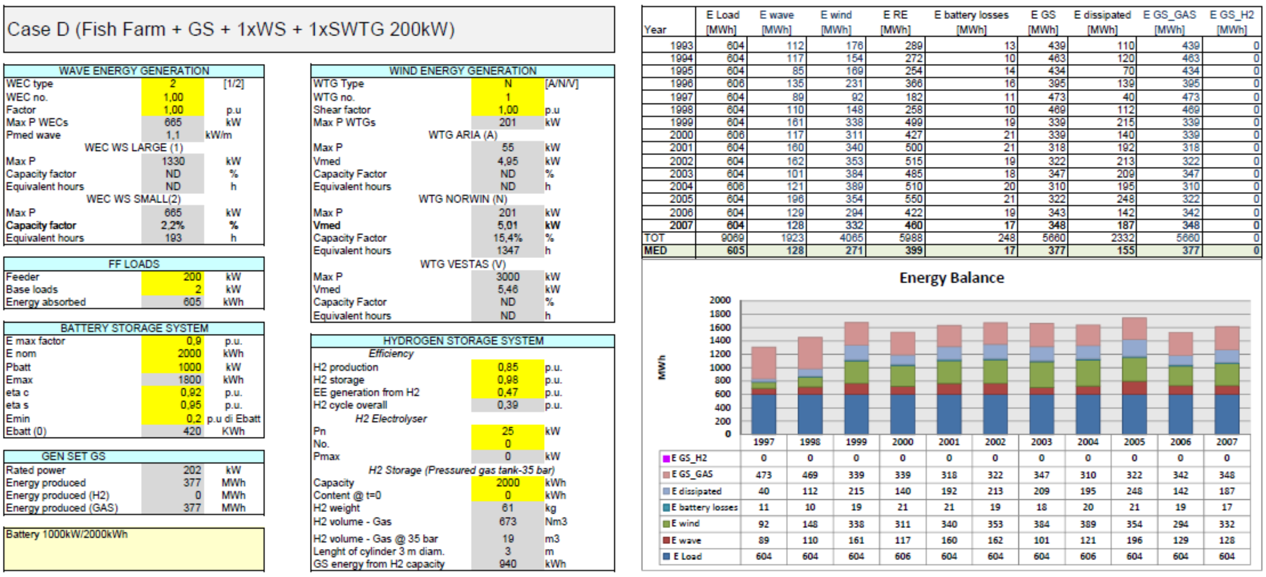
The current model version offers the possibility to choose between:

- two types of wave energy converter, one with a nominal power of 1.3MW and the other with a nominal power of 600kW;
- three types of wind turbine generators respectively one of large size 3MW, and two small ones: 200kW, 55kW;
- a characteristic fish-farm load profile with a settable power consumption variable on a three-hours base;
- a battery with a settable size, charge and discharge efficiency, maximum and minimum state of energy (SOE)
- a Hydrogen storage device that produces and stocks hydrogen from renewable hub generation that exceeds load needs and battery actual capacity
- a generator set fed by hydrogen and/or compressed natural gas that assure load coverage when the battery is empty and renewable generation is not enough.

The wave to wire model of wave energy converters has been developed by Università di Bologna: its numerical results, in terms of power related to each wave climate of the analysed time series has been inserted successfully in the hub model, for each of WECs configuration analysed.

Simplified wind to wire model, as well as storage systems and emergency generator sets modelling were carried out by Enel Research.

The tool, developed in form of Excel spreadsheet, is featured with a user interface for a quick and easy insertion of inputs and a synthetic representation of global annual energy generated, used and in excess at hub level as well annual energy managed by each hub device.



Case D (Fish Farm + GS + 1xWS + 1xSWTG 200kW)

WAVE ENERGY GENERATION		
WEC type	2	[1/2]
WEC no.	1,00	
Factor	1,00	p.u
Max P WECs	665	kW
Pmed wave	1,1	kW/m
WEC WS LARGE (1)		
Max P	1330	kW
Capacity factor	ND	%
Equivalent hours	ND	h
WEC WS SMALL(2)		
Max P	665	kW
Capacity factor	**2,2%**	**%**
Equivalent hours	193	h

FF LOADS		
Feeder	200	kW
Base loads	2	kW
Energy absorbed	605	kWh

BATTERY STORAGE SYSTEM		
E max factor	0,9	p.u.
E nom	2000	kWh
Pbatt	1000	kW
Emax	1800	kWh
eta c	0,92	p.u.
eta s	0,95	p.u.
Emin	0,2	p.u di Ebatt
Ebatt (0)	420	KWh

GEN SET GS		
Rated power	202	kW
Energy produced	377	MWh
Energy produced (H2)	0	MWh
Energy produced (GAS)	377	MWh

Battery 1000kW/2000kWh

WIND ENERGY GENERATION		
WTG Type	N	[A/N/V]
WTG no.	1	
Shear factor	1,00	p.u
Max P WTGs	201	kW
WTG ARIA (A)		
Max P	55	kW
Vmed	4,95	kW
Capacity Factor	ND	%
Equivalent hours	ND	h
WTG NORWIN (N)		
Max P	201	kW
Vmed	**5,01**	**kW**
Capacity Factor	15,4%	%
Equivalent hours	1347	h
WTG VESTAS (V)		
Max P	3000	kW
Vmed	5,46	kW
Capacity Factor	ND	%
Equivalent hours	ND	h

HYDROGEN STORAGE SYSTEM		
Efficiency		
H2 production	0,85	p.u.
H2 storage	0,98	p.u.
EE generation from H2	0,47	p.u.
H2 cycle overall	0,39	p.u.
H2 Electrolyser		
Pn	25	kW
No.	0	
Pmax	0	kW
H2 Storage (Pressured gas tank-35 bar)		
Capacity	2000	kWh
Content @ t=0	0	kWh
H2 weight	61	kg
H2 volume - Gas	673	Nm3
H2 volume - Gas @ 35 bar	19	m3
Lenght of cylinder 3 m diam.	3	m
GS energy from H2 capacity	940	kWh

Year	E Load [MWh]	E wave [MWh]	E wind [MWh]	E RE [MWh]	E battery losses [MWh]	E GS [MWh]	E dissipated [MWh]	E GS_GAS [MWh]	E GS_H2 [MWh]
1993	604	112	176	289	13	439	110	439	0
1994	604	117	154	272	10	463	120	463	0
1995	604	85	169	254	14	434	70	434	0
1996	606	135	231	366	16	395	139	395	0
1997	604	89	92	182	11	473	40	473	0
1998	604	110	148	258	10	469	112	469	0
1999	604	161	338	499	19	339	215	339	0
2000	606	117	311	427	21	339	140	339	0
2001	604	160	340	500	21	318	192	318	0
2002	604	162	353	515	19	322	213	322	0
2003	604	101	384	485	18	347	209	347	0
2004	606	121	389	510	20	310	195	310	0
2005	604	196	354	550	21	322	248	322	0
2006	604	129	294	422	19	343	142	342	0
2007	**604**	**128**	**332**	**460**	**17**	**348**	**187**	**348**	**0**
TOT	9069	1923	4065	5988	248	5660	2332	5660	0
MED	**605**	**128**	**271**	**399**	**17**	**377**	**155**	**377**	**0**

	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007
■ E GS_H2	0	0	0	0	0	0	0	0	0	0	0
■ E GS_GAS	473	469	339	339	318	322	347	310	322	342	348
■ E dissipated	40	112	215	140	192	213	209	195	248	142	187
■ E battery losses	11	10	19	21	21	19	18	20	21	19	17
■ E wind	92	148	338	311	340	353	384	389	354	294	332
■ E wave	89	110	161	117	160	162	101	121	196	129	128
■ E Load	604	604	604	606	604	604	604	606	604	604	604

Figure 97. User interface for input insertion and synthetic representation of results of stationary analysis.

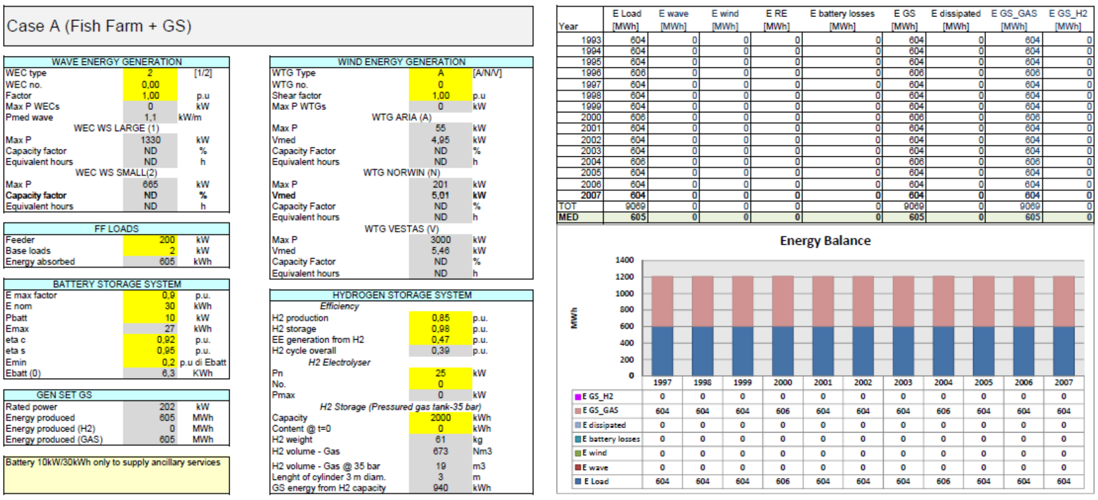
For grid connected solution the exported power is computed as the excess of generated power with respect to the local loads: a reduction factor associated to the power losses of the grid connection technology selected in accordance with the parameters Power and Distance to shore of the offshore platforms indicated in deliverable 3.4.1, is also taken into account.

With this model, it is simple to compare different configuration/layout over long time period in order to select the one that maximize renewable resources utilization. The maximum number of time series records that can be analysed by the model is limited only by the capacity of the excel spreadsheet.

The model is also featured by a cost analysis module in order to support the evaluation of economic feasibility of each considered platform configuration.

The model is under application on WT 7.4 Mediterranean site and has been tested on the following case studies:

- Case A- offshore fish farm with electrical loads supplied by a diesel generator set.



Case A (Fish Farm + GS)

WAVE ENERGY GENERATION		
WEC type	2	[1/2]
WEC no.	0,00	
Factor	1,00	p.u
Max P WECs	0	kW
Pmed wave	1,1	kW/m
WEC WS LARGE (1)		
Max P	1330	kW
Capacity factor	ND	%
Equivalent hours	ND	h
WEC WS SMALL(2)		
Max P	665	kW
Capacity factor	**ND**	**%**
Equivalent hours	ND	h

FF LOADS		
Feeder	200	kW
Base loads	2	kW
Energy absorbed	605	kWh

BATTERY STORAGE SYSTEM		
E max factor	0,9	p.u.
E nom	30	kWh
Pbatt	10	kW
Emax	27	kWh
eta c	0,92	p.u.
eta s	0,95	p.u.
Emin	0,2	p.u di Ebatt
Ebatt (0)	6,3	KWh

GEN SET GS		
Rated power	202	kW
Energy produced	605	MWh
Energy produced (H2)	0	MWh
Energy produced (GAS)	605	MWh

Battery 10kW/30kWh only to supply ancillary services

WIND ENERGY GENERATION		
WTG Type	A	[A/N/V]
WTG no.	0	
Shear factor	1,00	p.u
Max P WTGs	0	kW
WTG ARIA (A)		
Max P	55	kW
Vmed	4,95	kW
Capacity Factor	ND	%
Equivalent hours	ND	h
WTG NORWIN (N)		
Max P	201	kW
Vmed	**5,01**	**kW**
Capacity Factor	ND	%
Equivalent hours	ND	h
WTG VESTAS (V)		
Max P	3000	kW
Vmed	5,46	kW
Capacity Factor	ND	%
Equivalent hours	ND	h

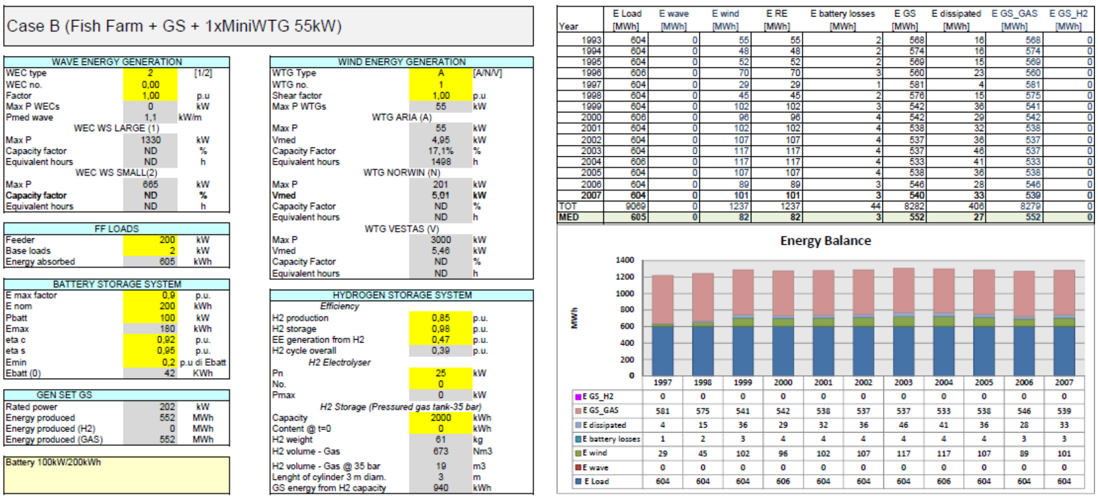
HYDROGEN STORAGE SYSTEM		
Efficiency		
H2 production	0,85	p.u.
H2 storage	0,98	p.u.
EE generation from H2	0,47	p.u.
H2 cycle overall	0,39	p.u.
H2 Electrolyser		
Pn	25	kW
No.	0	
Pmax	0	kW
H2 Storage (Pressured gas tank-35 bar)		
Capacity	2000	kWh
Content @ t=0	0	kWh
H2 weight	61	kg
H2 volume - Gas	673	Nm3
H2 volume - Gas @ 35 bar	19	m3
Lenght of cylinder 3 m diam.	3	m
GS energy from H2 capacity	940	kWh

Year	E Load [MWh]	E wave [MWh]	E wind [MWh]	E RE [MWh]	E battery losses [MWh]	E GS [MWh]	E dissipated [MWh]	E GS_GAS [MWh]	E GS_H2 [MWh]
1993	604	0	0	0	0	604	0	604	0
1994	604	0	0	0	0	604	0	604	0
1995	604	0	0	0	0	604	0	604	0
1996	606	0	0	0	0	606	0	606	0
1997	604	0	0	0	0	604	0	604	0
1998	604	0	0	0	0	604	0	604	0
1999	604	0	0	0	0	604	0	604	0
2000	606	0	0	0	0	606	0	606	0
2001	604	0	0	0	0	604	0	604	0
2002	604	0	0	0	0	604	0	604	0
2003	604	0	0	0	0	604	0	604	0
2004	606	0	0	0	0	606	0	606	0
2005	604	0	0	0	0	604	0	604	0
2006	604	0	0	0	0	604	0	604	0
2007	**604**	**0**	**0**	**0**	**0**	**604**	**0**	**604**	**0**
TOT	9069	0	0	0	0	9069	0	9069	0
MED	605	0	0	0	0	605	0	605	0

Energy Balance

	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007
E GS_H2	0	0	0	0	0	0	0	0	0	0	0
E GS_GAS	604	604	604	606	604	604	604	606	604	604	604
E dissipated	0	0	0	0	0	0	0	0	0	0	0
E battery losses	0	0	0	0	0	0	0	0	0	0	0
E wind	0	0	0	0	0	0	0	0	0	0	0
E wave	0	0	0	0	0	0	0	0	0	0	0
E Load	604	604	604	606	604	604	604	606	604	604	604

- Case B- offshore fish farm with electrical loads supplied by a diesel generator set and a wind turbine of 55kW



Case B (Fish Farm + GS + 1xMiniWTG 55kW)

WAVE ENERGY GENERATION		
WEC type	2	[1/2]
WEC no.	0,00	
Factor	1,00	p.u
Max P WECs	0	kW
Pmed wave	1,1	kW/m
WEC WS LARGE (1)		
Max P	1330	kW
Capacity factor	ND	%
Equivalent hours	ND	h
WEC WS SMALL(2)		
Max P	665	kW
Capacity factor	**ND**	**%**
Equivalent hours	ND	h

FF LOADS		
Feeder	200	kW
Base loads	2	kW
Energy absorbed	605	kWh

BATTERY STORAGE SYSTEM		
E max factor	0,9	p.u.
E nom	200	kWh
Pbatt	100	kW
Emax	180	kWh
eta c	0,92	p.u.
eta s	0,95	p.u.
Emin	0,2	p.u di Ebatt
Ebatt (0)	42	KWh

GEN SET GS		
Rated power	202	kW
Energy produced	552	MWh
Energy produced (H2)	0	MWh
Energy produced (GAS)	552	MWh

Battery 100kW/200kWh

WIND ENERGY GENERATION		
WTG Type	A	[A/N/V]
WTG no.	1	
Shear factor	1,00	p.u
Max P WTGs	55	kW
WTG ARIA (A)		
Max P	55	kW
Vmed	4,95	kW
Capacity Factor	17,1%	%
Equivalent hours	1498	h
WTG NORWIN (N)		
Max P	201	kW
Vmed	**5,01**	**kW**
Capacity Factor	ND	%
Equivalent hours	ND	h
WTG VESTAS (V)		
Max P	3000	kW
Vmed	5,46	kW
Capacity Factor	ND	%
Equivalent hours	ND	h

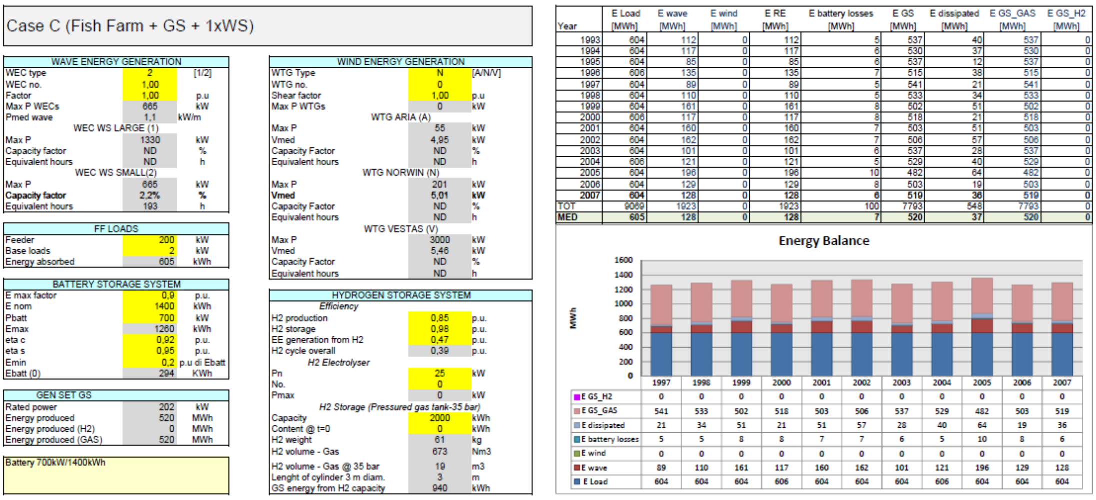
HYDROGEN STORAGE SYSTEM		
Efficiency		
H2 production	0,85	p.u.
H2 storage	0,98	p.u.
EE generation from H2	0,47	p.u.
H2 cycle overall	0,39	p.u.
H2 Electrolyser		
Pn	25	kW
No.	0	
Pmax	0	kW
H2 Storage (Pressured gas tank-35 bar)		
Capacity	2000	kWh
Content @ t=0	0	kWh
H2 weight	61	kg
H2 volume - Gas	673	Nm3
H2 volume - Gas @ 35 bar	19	m3
Lenght of cylinder 3 m diam.	3	m
GS energy from H2 capacity	940	kWh

Year	E Load [MWh]	E wave [MWh]	E wind [MWh]	E RE [MWh]	E battery losses [MWh]	E GS [MWh]	E dissipated [MWh]	E GS_GAS [MWh]	E GS_H2 [MWh]
1993	604	0	55	55	2	568	16	568	0
1994	604	0	48	48	2	574	16	574	0
1995	604	0	52	52	2	569	15	569	0
1996	606	0	70	70	3	560	23	560	0
1997	604	0	29	29	1	581	4	581	0
1998	604	0	45	45	2	576	15	575	0
1999	604	0	102	102	3	542	36	541	0
2000	606	0	96	96	4	542	29	542	0
2001	604	0	102	102	4	538	32	538	0
2002	604	0	107	107	4	537	36	537	0
2003	604	0	117	117	4	537	46	537	0
2004	606	0	117	117	4	533	41	533	0
2005	604	0	107	107	4	538	36	538	0
2006	604	0	89	89	3	546	28	546	0
2007	**604**	**0**	**101**	**101**	**3**	**540**	**33**	**539**	**0**
TOT	9069	0	1237	1237	44	8282	406	8279	0
MED	605	0	82	82	3	552	27	552	0

Energy Balance

	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007
E GS_H2	0	0	0	0	0	0	0	0	0	0	0
E GS_GAS	581	575	541	542	538	537	537	533	538	546	539
E dissipated	4	15	36	29	32	36	46	41	36	28	33
E battery losses	1	2	3	4	4	4	4	4	4	3	3
E wind	29	45	102	96	102	107	117	117	107	89	101
E wave	0	0	0	0	0	0	0	0	0	0	0
E Load	604	604	604	606	604	604	604	606	604	604	604

- Case C: offshore fish farm with electrical loads supplied by a diesel generator set and a wave energy converter of 665kW



Case C (Fish Farm + GS + 1xWS)

WAVE ENERGY GENERATION

WEC type	2	[1/2]
WEC no.	1,00	
Factor	1,00	p.u
Max P WECs	665	kW
Pmed wave	1,1	kW/m
WEC WS LARGE (1)		
Max P	1330	kW
Capacity factor	ND	%
Equivalent hours	ND	h
WEC WS SMALL(2)		
Max P	665	kW
Capacity factor	**2,2%**	**%**
Equivalent hours	193	h

FF LOADS

Feeder	200	kW
Base loads	2	kW
Energy absorbed	605	kWh

BATTERY STORAGE SYSTEM

E max factor	0,9	p.u.
E nom	1400	kWh
Pbatt	700	kW
Emax	1260	kWh
eta c	0,92	p.u.
eta s	0,95	p.u.
Emin	0,2	p.u di Ebatt
Ebatt (0)	294	KWh

GEN SET GS

Rated power	202	kW
Energy produced	520	MWh
Energy produced (H2)	0	MWh
Energy produced (GAS)	520	MWh

Battery 700kW/1400kWh

WIND ENERGY GENERATION

WTG Type	N	[A/N/V]
WTG no.	0	
Shear factor	1,00	p.u
Max P WTGs	0	kW
WTG ARIA (A)		
Max P	55	kW
Vmed	4,95	kW
Capacity Factor	ND	%
Equivalent hours	ND	h
WTG NORWIN (N)		
Max P	201	kW
Vmed	**5,01**	**kW**
Capacity Factor	ND	%
Equivalent hours	ND	h
WTG VESTAS (V)		
Max P	3000	kW
Vmed	5,46	kW
Capacity Factor	ND	%
Equivalent hours	ND	h

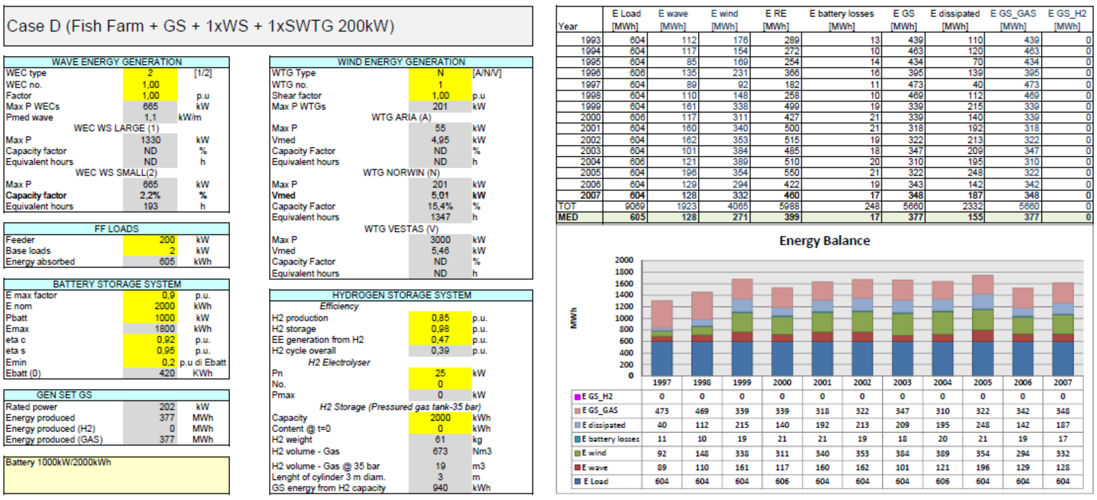
HYDROGEN STORAGE SYSTEM

Efficiency		
H2 production	0,85	p.u.
H2 storage	0,98	p.u.
EE generation from H2	0,47	p.u.
H2 cycle overall	0,39	p.u.
H2 Electrolyser		
Pn	25	kW
No.	0	
Pmax	0	kW
H2 Storage (Pressured gas tank-35 bar)		
Capacity	2000	kWh
Content @ t=0	0	kWh
H2 weight	61	kg
H2 volume - Gas	673	Nm3
H2 volume - Gas @ 35 bar	19	m3
Lenght of cylinder 3 m diam.	3	m
GS energy from H2 capacity	940	kWh

Year	E Load [MWh]	E wave [MWh]	E wind [MWh]	E RE [MWh]	E battery losses [MWh]	E GS [MWh]	E dissipated [MWh]	E GS_GAS [MWh]	E GS_H2 [MWh]
1993	604	112	0	112	5	537	40	537	0
1994	604	117	0	117	6	530	37	530	0
1995	604	85	0	85	6	537	12	537	0
1996	606	135	0	135	7	515	38	515	0
1997	604	89	0	89	5	541	21	541	0
1998	604	110	0	110	5	533	34	533	0
1999	604	161	0	161	8	502	51	502	0
2000	606	117	0	117	8	518	21	518	0
2001	604	160	0	160	7	503	51	503	0
2002	604	162	0	162	7	506	57	506	0
2003	604	101	0	101	6	537	28	537	0
2004	606	121	0	121	5	529	40	529	0
2005	604	196	0	196	10	482	64	482	0
2006	604	129	0	129	8	503	19	503	0
2007	**604**	**128**	**0**	**128**	**6**	**519**	**36**	**519**	**0**
TOT	9069	1923	0	1923	100	7793	548	7793	0
MED	**605**	**128**	**0**	**128**	**7**	**520**	**37**	**520**	**0**

	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007
E GS_H2	0	0	0	0	0	0	0	0	0	0	0
E GS_GAS	541	533	502	518	503	506	537	529	482	503	519
E dissipated	21	34	51	21	51	57	28	40	64	19	36
E battery losses	5	5	8	8	7	7	6	5	10	8	6
E wind	0	0	0	0	0	0	0	0	0	0	0
E wave	89	110	161	117	160	162	101	121	196	129	128
E Load	604	604	604	606	604	604	604	606	604	604	604

- Case D: offshore fish farm with electrical loads supplied by a diesel generator set, a wave energy converter of 665kW and a wind turbine of 200kW



Case D (Fish Farm + GS + 1xWS + 1xSWTG 200kW)

WAVE ENERGY GENERATION

WEC type	2	[1/2]
WEC no.	1,00	
Factor	1,00	p.u
Max P WECs	665	kW
Pmed wave	1,1	kW/m
WEC WS LARGE (1)		
Max P	1330	kW
Capacity factor	ND	%
Equivalent hours	ND	h
WEC WS SMALL(2)		
Max P	665	kW
Capacity factor	**2,2%**	**%**
Equivalent hours	193	h

FF LOADS

Feeder	200	kW
Base loads	2	kW
Energy absorbed	605	kWh

BATTERY STORAGE SYSTEM

E max factor	0,9	p.u.
E nom	2000	kWh
Pbatt	1000	kW
Emax	1800	kWh
eta c	0,92	p.u.
eta s	0,95	p.u.
Emin	0,2	p.u di Ebatt
Ebatt (0)	420	KWh

GEN SET GS

Rated power	202	kW
Energy produced	377	MWh
Energy produced (H2)	0	MWh
Energy produced (GAS)	377	MWh

Battery 1000kW/2000kWh

WIND ENERGY GENERATION

WTG Type	N	[A/N/V]
WTG no.	1	
Shear factor	1,00	p.u
Max P WTGs	201	kW
WTG ARIA (A)		
Max P	55	kW
Vmed	4,95	kW
Capacity Factor	ND	%
Equivalent hours	ND	h
WTG NORWIN (N)		
Max P	201	kW
Vmed	**5,01**	**kW**
Capacity Factor	15,4%	%
Equivalent hours	1347	h
WTG VESTAS (V)		
Max P	3000	kW
Vmed	5,46	kW
Capacity Factor	ND	%
Equivalent hours	ND	h

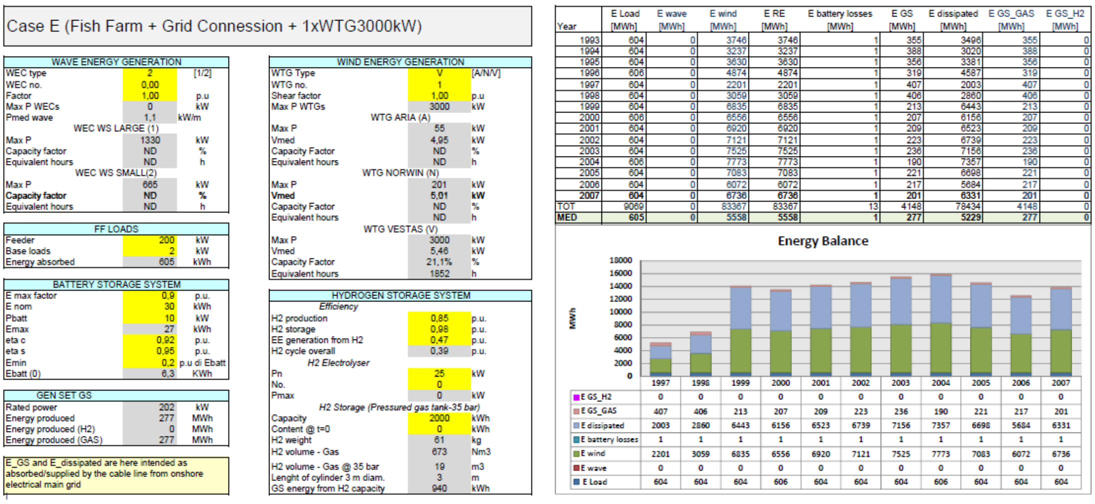
HYDROGEN STORAGE SYSTEM

Efficiency		
H2 production	0,85	p.u.
H2 storage	0,98	p.u.
EE generation from H2	0,47	p.u.
H2 cycle overall	0,39	p.u.
H2 Electrolyser		
Pn	25	kW
No.	0	
Pmax	0	kW
H2 Storage (Pressured gas tank-35 bar)		
Capacity	2000	kWh
Content @ t=0	0	kWh
H2 weight	61	kg
H2 volume - Gas	673	Nm3
H2 volume - Gas @ 35 bar	19	m3
Lenght of cylinder 3 m diam.	3	m
GS energy from H2 capacity	940	kWh

Year	E Load [MWh]	E wave [MWh]	E wind [MWh]	E RE [MWh]	E battery losses [MWh]	E GS [MWh]	E dissipated [MWh]	E GS_GAS [MWh]	E GS_H2 [MWh]
1993	604	112	176	289	13	439	110	439	0
1994	604	117	154	272	10	463	120	463	0
1995	604	85	169	254	14	434	70	434	0
1996	606	135	231	366	16	395	139	395	0
1997	604	89	92	182	11	473	40	473	0
1998	604	110	148	258	10	469	112	469	0
1999	604	161	338	499	19	339	215	339	0
2000	606	117	311	427	21	339	140	339	0
2001	604	160	340	500	21	318	192	318	0
2002	604	162	353	515	19	322	213	322	0
2003	604	101	384	485	18	347	209	347	0
2004	606	121	389	510	20	310	195	310	0
2005	604	196	354	550	21	322	248	322	0
2006	604	129	294	422	19	343	142	342	0
2007	**604**	**128**	**332**	**460**	**17**	**348**	**187**	**348**	**0**
TOT	9069	1923	4065	5988	248	5660	2332	5660	0
MED	**605**	**128**	**271**	**399**	**17**	**377**	**155**	**377**	**0**

	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007
E GS_H2	0	0	0	0	0	0	0	0	0	0	0
E GS_GAS	473	469	339	339	318	322	347	310	322	342	348
E dissipated	40	112	215	140	192	213	209	195	248	142	187
E battery losses	11	10	19	21	21	19	18	20	21	19	17
E wind	92	148	338	311	340	353	384	389	354	294	332
E wave	89	110	161	117	160	162	101	121	196	129	128
E Load	604	604	604	606	604	604	604	606	604	604	604

- Case E: offshore fish farm with a wind turbine of 3MW, connected to the grid



Case E (Fish Farm + Grid Connession + 1xWTG3000kW)

WAVE ENERGY GENERATION		
WEC type	2	[1/2]
WEC no.	0,00	
Factor	1,00	p.u
Max P WECs	0	kW
Pmed wave	1,1	kW/m
WEC WS LARGE (1)		
Max P	1330	kW
Capacity factor	ND	%
Equivalent hours	ND	h
WEC WS SMALL(2)		
Max P	665	kW
Capacity factor	**ND**	**%**
Equivalent hours	ND	h

FF LOADS		
Feeder	200	kW
Base loads	2	kW
Energy absorbed	605	kWh

BATTERY STORAGE SYSTEM		
E max factor	0,9	p.u.
E nom	30	kWh
Pbatt	10	kW
Emax	27	kWh
eta c	0,92	p.u.
eta s	0,95	p.u.
Emin	0,2	p.u di Ebatt
Ebatt (0)	6,3	KWh

GEN SET GS		
Rated power	202	kW
Energy produced	277	MWh
Energy produced (H2)	0	MWh
Energy produced (GAS)	277	MWh

E_GS and E_dissipated are here intended as absorbed/supplied by the cable line from onshore electrical main grid

WIND ENERGY GENERATION		
WTG Type	V	[A/N/V]
WTG no.	1	
Shear factor	1,00	p.u
Max P WTGs	3000	kW
WTG ARIA (A)		
Max P	55	kW
Vmed	4,95	kW
Capacity Factor	ND	%
Equivalent hours	ND	h
WTG NORWIN (N)		
Max P	201	kW
Vmed	**5,01**	**kW**
Capacity Factor	ND	%
Equivalent hours	ND	h
WTG VESTAS (V)		
Max P	3000	kW
Vmed	5,46	kW
Capacity Factor	21,1%	%
Equivalent hours	1852	h

HYDROGEN STORAGE SYSTEM		
Efficiency		
H2 production	0,85	p.u.
H2 storage	0,98	p.u.
EE generation from H2	0,47	p.u.
H2 cycle overall	0,39	p.u.
H2 Electrolyser		
Pn	25	kW
No.	0	
Pmax	0	kW
H2 Storage (Pressured gas tank-35 bar)		
Capacity	2000	kWh
Content @ t=0	0	kWh
H2 weight	61	kg
H2 volume - Gas	673	Nm3
H2 volume - Gas @ 35 bar	19	m3
Lenght of cylinder 3 m diam.	3	m
GS energy from H2 capacity	940	kWh

Year	E Load [MWh]	E wave [MWh]	E wind [MWh]	E RE [MWh]	E battery losses [MWh]	E GS [MWh]	E dissipated [MWh]	E GS_GAS [MWh]	E GS_H2 [MWh]
1993	604	0	3746	3746	1	355	3496	355	0
1994	604	0	3237	3237	1	388	3020	388	0
1995	604	0	3630	3630	1	356	3381	356	0
1996	606	0	4874	4874	1	319	4587	319	0
1997	604	0	2201	2201	1	407	2003	407	0
1998	604	0	3059	3059	1	406	2860	406	0
1999	604	0	6835	6835	1	213	6443	213	0
2000	606	0	6556	6556	1	207	6156	207	0
2001	604	0	6920	6920	1	209	6523	209	0
2002	604	0	7121	7121	1	223	6739	223	0
2003	604	0	7525	7525	1	236	7156	236	0
2004	606	0	7773	7773	1	190	7357	190	0
2005	604	0	7083	7083	1	221	6698	221	0
2006	604	0	6072	6072	1	217	5684	217	0
2007	**604**	**0**	**6736**	**6736**	**1**	**201**	**6331**	**201**	**0**
TOT	9069	0	83367	83367	13	4148	78434	4148	0
MED	**605**	**0**	**5558**	**5558**	**1**	**277**	**5229**	**277**	**0**

Energy Balance

	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007
E GS_H2	0	0	0	0	0	0	0	0	0	0	0
E GS_GAS	407	406	213	207	209	223	236	190	221	217	201
E dissipated	2003	2860	6443	6156	6523	6739	7156	7357	6698	5684	6331
E battery losses	1	1	1	1	1	1	1	1	1	1	1
E wind	2201	3059	6835	6556	6920	7121	7525	7773	7083	6072	6736
E wave	0	0	0	0	0	0	0	0	0	0	0
E Load	604	604	604	606	604	604	604	606	604	604	604

4 Application Case: Design a new multi-use platform at Cantabria Offshore Site (COS)

A new multi-use offshore platform have been developed for COS using all information generated during the Mermaid project in work package 3 (platform technology and energy converters), 4 (aquaculture analysis) and 5 (geotechnical constraints). The new multi-use platform is a semi-submersible floating platform formed by three oscillating water column (OWC) and one wind turbine.

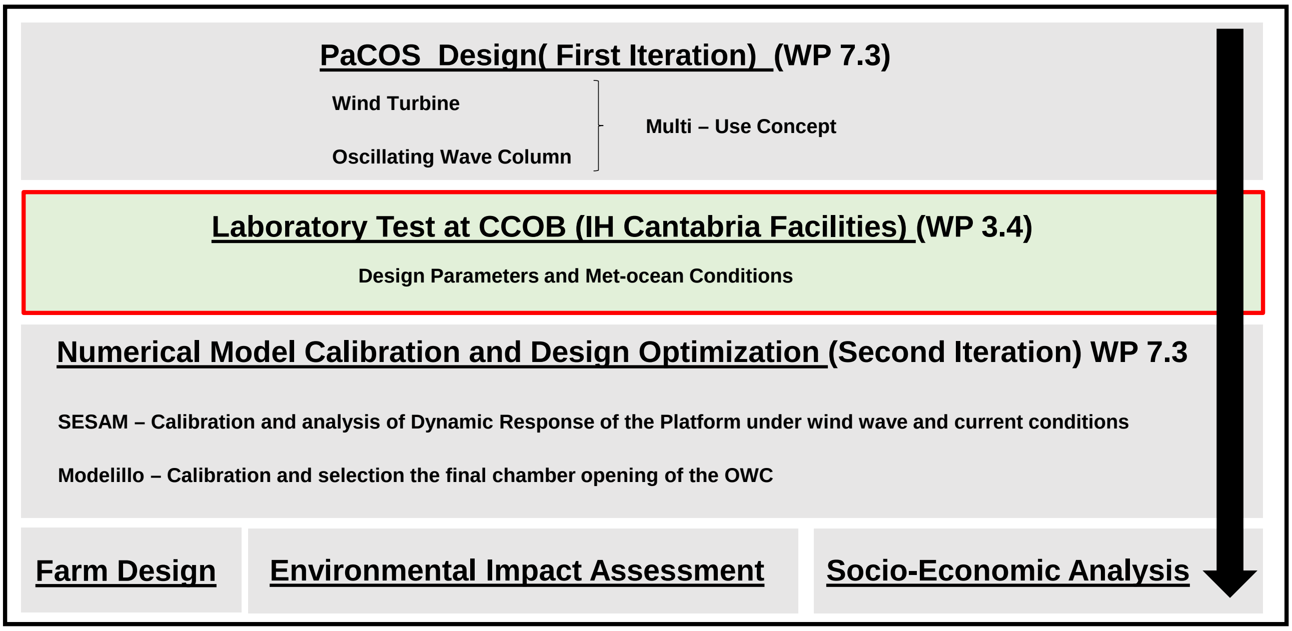
During this section, the final design of platform at COS will be presented, as well as, the work program of laboratory test designed to be able to validate the final design. The numerical model employed to validate platform design will be SESAM and one simplified time domain model developed at IH Cantabria.

SESAM will be used to validate and to check the behavior of the offshore platform under action of wind, wave and current. Different sea state will be simulated with SESAM in order to know the dynamic response of the platform and loads on the mooring system.

On the other hand, the wave energy production generated by the OWC (oscillating water columns) of the platform, will be analyzed through the simplify time domain model called “IH-wave2wire”. IH-wave2wire numerical model will be used to optimize the chambers opening of OWC, taken into account the relation between wave energy production and stability of the floating platform.

The results obtained from laboratory test, as well as, the simulation done with SESAM and IH-wave2wire will be carried out, analyzed and incorporated in the deliverable WP7.3, where one of the main goals is to design the most suitable multi-use offshore energy farm for Cantabria Offshore Site.

The methodology shown in Figure 14, has been employed to design the MUP. The Table 22 shows the steps to design the multi-use farm at COS site, as well as, the relation between deliverable 3.4 and 7.3 (farm at COS site).



PaCOS Design(First Iteration) (WP 7.3)

Wind Turbine
Oscillating Wave Column
Multi – Use Concept

Laboratory Test at CCOB (IH Cantabria Facilities) (WP 3.4)

Design Parameters and Met-ocean Conditions

Numerical Model Calibration and Design Optimization (Second Iteration) WP 7.3

SESAM – Calibration and analysis of Dynamic Response of the Platform under wind wave and current conditions

Modelillo – Calibration and selection the final chamber opening of the OWC

Farm Design | **Environmental Impact Assessment** | **Socio-Economic Analysis**

Table 22. Methodology to design MUP at COS.

4.1 MUP Description

The final MUP design proposed for the Atlantic site combines the uses of wind and wave energy converters. This new design is a semi-submersible floating platform formed by three oscillating water column (OWC) and one horizontal wind turbine (Figure 98).

The base of the floating structure is formed by a heave plate to support the different platform elements (even wave energy converters and wind turbine) and to give more hydrodynamic stability. The multi-use platform base view from above is an equilateral triangle.

Over the heave plate, four columns/floaters are placed to give to the platform the buoyancy required. Three of four cylinders are located in the vertex of the base, while the other one is in the center of the base. The four columns are connected between them by beams with rectangular section.

The oscillating water columns (OWCs) are located around of the columns supported over the vertex of the heave plate, while the wind turbines is supported to the central column.

Furthermore, the MUP has available an active ballast system (water) in the columns to reduce the rotations due to thrust wind forces applied over the wind turbine.

The floating platform is anchored to the seabed by means of a mooring system formed by 4 catenary lines (weight 186 Kg/m and length 400 m).

The whole structure (full prototype) has been designed to be made in concrete.

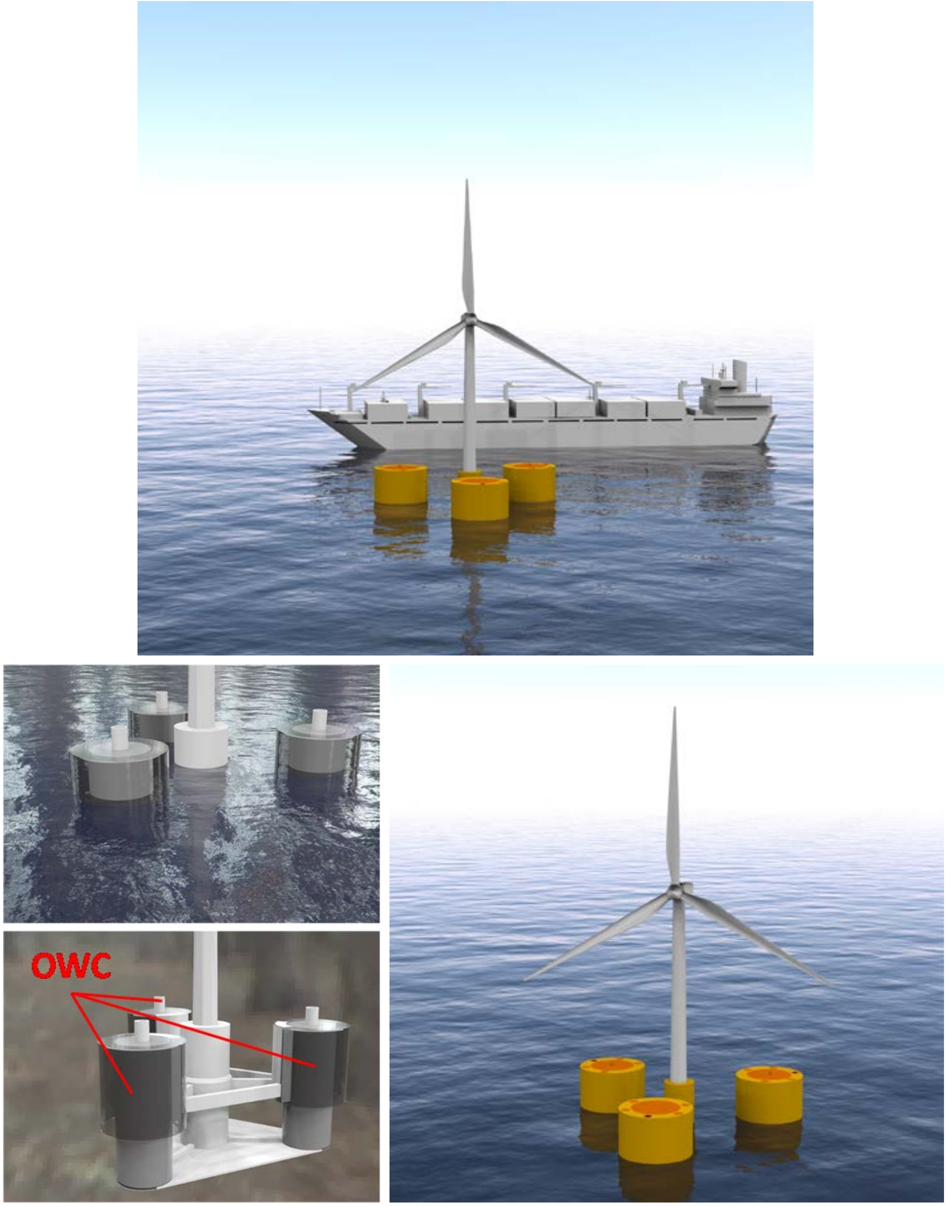


Figure 98. Atlantic site MUP: Final design.

The main characteristics of the floating MUP are summarized in table (Table 23). It can highlighted the power capacity, which is around 8MW.

Table 23. Main characteristics of the MUP proposed for Cantabria Offshore Site.

PaCOS Platform Cantabria Offshore Site		
Main characteristics	**Units**	**Dimension**
Platform Mass	Kg	8931262
Platform Draft	m	18
Diameter of Vertex floating Cylinder	m	11,97
Diameter of Central floating Cylinder	m	8,015
Side of heave plate (Equilateral Triangle)	m	65,905
Gravity Center from the base line	m	15,47
Wind Turbine	MW	NREL 5 MW
Capacity of each Oscillating Water Column	KW	1150 KW
External Diameter of OWC	m	17,99
Internal Diameter of OWC	m	11,97
Water Depth	m	105
Mooring System Weight	kg/m	186
Length of Mooring System	m	400
Number of Lines	m	4

4.2 Laboratory Test

The physical model tests are proposed to be executed in the Cantabria Coastal & Ocean Basin (CCOB), described in detail in WP7.3. The present section summarizes the test proposal.

The platform made to laboratory test at CCOB has been scaled taken account into the Froude Scaling.

Considering the geometry of the structure, the target water depth, the mooring system footprint, and the size of IH Cantabria facilities, the most suitable scale will be **1/35.**

The material used to build the platform model will be steel. The material thickness and weight of the sections will be adjusted to maintain the weight distribution imposed by the geometric scale once the instrumentation is installed.

The prototype rotor will be simulated using a previously calibrated spinning actuator disk. It will represent the corresponding wind load as well as the gyroscopic effects due to the rotation of the wind turbine. The weight of the disc and motor set will be at geometric scale (λ^3) of the total weight of the rotor and nacelle at prototype scale.

The general goals of the laboratory test program are:

1. To determine experimentally the Response Amplitude Operator of the structure in the frequency range given by the results obtained by a numerical model.

2. To analyze the dynamic response of the structure under operating conditions combining wave, wind and current action over the floating platform.

3. To study the performance of the structure under extreme conditions (wave, wind and wind) with the turbine out of operation (parked).

4. To create a calibration/validation data set for calibration of SESAM.

5. To create a calibration data set for IH-wave2wire to be able optimize the chamber opening of the OWC

According to the previously stated goals, the specific objectives of this work are:

1. To build a reduced scale physical model of the concept, including the substructure, the mooring system, the tower and a dummy nacelle with an actuator disk based on the turbine performance.

2. To carry out the necessary tests to calibrate the critical parameters, including those related to the response of the mooring system in terms of stiffness and damping.

3. To carry out the necessary tests for selected combinations of external loads (waves, wind and current) to verify the motions and accelerations of the device, as well as dynamic loads on the mooring lines under operational and survival sea state.

COS platform will be tested with four different chamber opening of the OWC. The openings of the OWC are shown in the Figure 99**.**

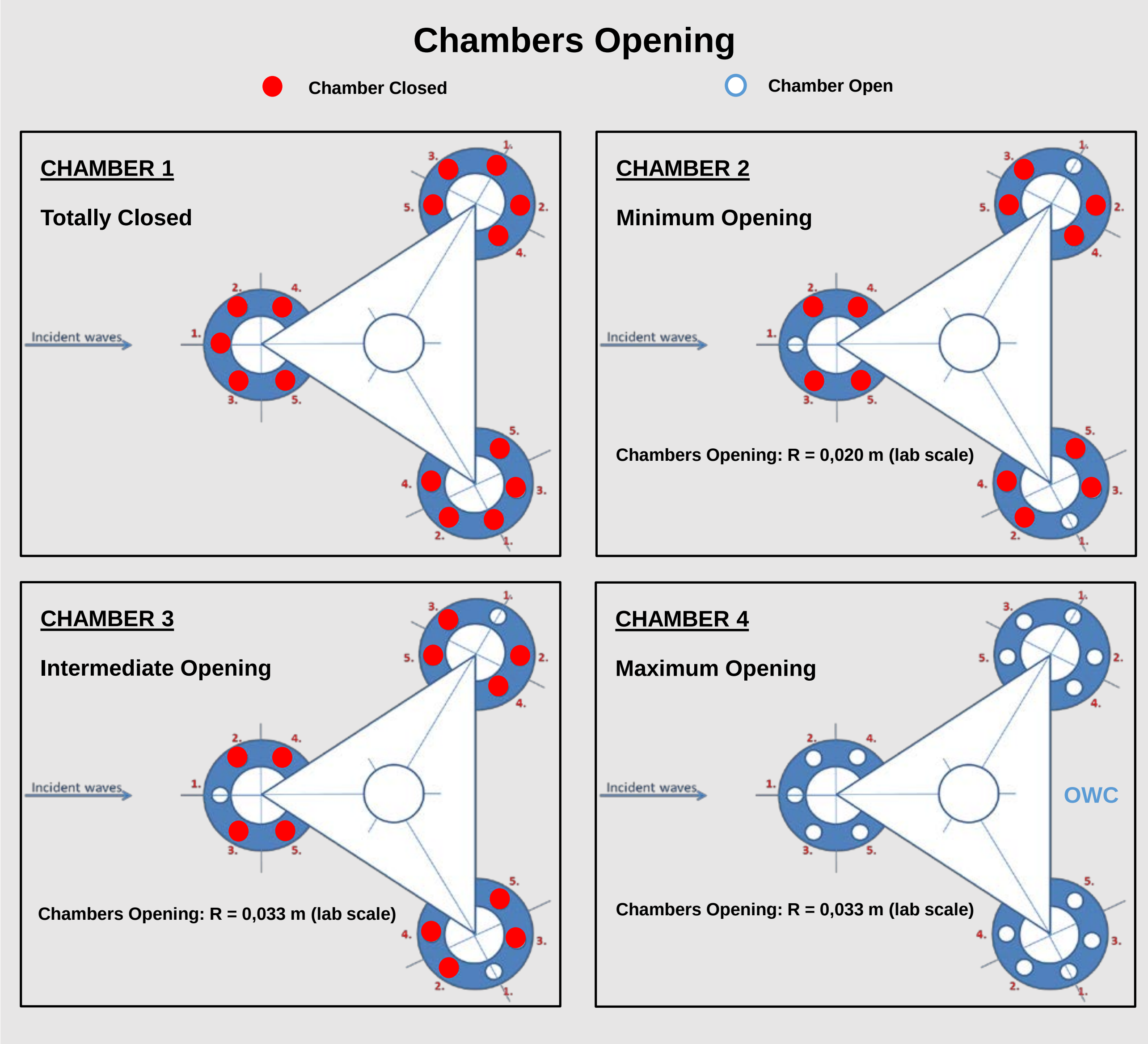


Figure 99. Configurations: Chamber Opening.

In addition to Figure 99 the four chamber opening can be summarizes on the following list:

- Configuration 1 - Chamber 1: Totally Closed
- Configuration 2 - Chamber 2: Minimum Opening (R = 0.02 m, laboratory scale)
- Configuration 3 - Chamber 3: Intermediate Opening (R = 0.033 m, laboratory scale)
- Configuration 4 - Chamber 4: Maximum Opening (R = 0.033 m, laboratory scale)

The MUP tests will be carried out with four different chambers opening, these four configurations will enable us to obtain a great data base to calibrate the numerical model based of simplified time domain model (“IH-wave2wire”).

The optimization of the OWC chambers will be done through the results obtained with the “IH-wave2wire” numerical model. The devices placed in the final offshore farm at COS will include the optimal chambers opening of OWC obtained through IH-wave2wire numerical model.

During laboratory work program, different test will be done in order to characterize the hydrodynamic response of the platform and the wave energy production. A brief description of test can be summarize on the following list:

1. Identification Test
   1.1. Weight Distribution test.
   1.2. Chamber sealing verification.
   1.3. Immersion and Inclining Test.
   1.4. Towing Test.
   1.5. Mooring Stiffness test (Static offset test).
   1.6. Decay Test without/with mooring system.

2. Regular Wave Test (with wind and without wind).
   2.1. Regular Wave Test: Only Wave.
   2.2. Regular Wave Test with wind.

3. Irregular Test.
   3.1. Irregular Wave Test: Only Waves.
   3.2. Irregular Wave + Current Test.
   3.3. Operational Sea State: Waves + Wind + (Currents).
   3.4. Survival Sea State: Waves + Wind + Current.

Different tests will be done with the different chamber opening shown above. In the following sections, a comprehensive description of the test will be done.

The sea state selected for the laboratory test have been chosen taken into account the information available in Work task 3.1 where met-ocean conditions exiting at Cantabria offshore site were described. During the following points, the sea state selected will be shown. The sea state generated during the laboratory test will be formed by the combination of wave-wind and current.

4.2.1 Identification test

4.2.1.1 Weight distribution test

The objective of this test is to check that the weight distribution of the model, how it has been built corresponds to the scaled prototype, i.e. is a quality control in which the scaled model has been constructed according to the specifications.
It would have the following task:

- Mass measurement of the model
- Determination of the model CDG
- Checking the geometry of the model

4.2.1.2 Immersion and inclination test

The objective of these tests is to check that the centers of flotation and the metacenter of the as built model. The next 4 configurations will be tested:

- Sealing of the model
- Buoyancy
- Verticality of the model
- Determination of the metacentric height (GM) – Roll and Pitch For **Chamber configuration 4 (Totally Open)**

INCLINING TEST			
D.O.F.	**RESULTS**	**Column ballast C1, C2, C3**	**CONFIGURATION 4 (Totally Open) Orifice R1, R2, R3, R4, R5 (m)**
Pitch	metacentric height GM	95, 95, 95	0,033 / 0,033 / 0,033 / 0,033 / 0,033
Roll		95, 95, 95	0,033 / 0,033 / 0,033 / 0,033 / 0,033

Table 24. Inclining Test.

4.2.1.3 Ballast and load test

The model will be ballasted up to the designed waterline, including trim and heel, and also match the center of gravity.

The moments of inertia will be determined by ITTC-7.5-02-07-03.1 - Recommended Procedures and Guidelines (Floating Offshore Platform Experiments).

4.2.1.4 Towing Tests

The objective of these tests is to determine the hydrodynamic drag coefficients of the MUP. The coefficients will be empirically determined. This will allow subsequent numerical model calibration of the current forces.

Test procedure and data analysis

- Installation of a controlled towing device of the structure
- On calm water the structure is towed with constant speed
- Force is monitored with a load cell
- Drag coefficient is estimated from the speed and the force recorded

At least, 4 current velocities will be tested: 2, 4, 6, 8 knots (Full-scale). The drag direction will be of 0 degrees.

The configuration employ to execute the towing test will be ***Configuration 4 (Chambers totally open).***

The Table 25 shows the towing test will be carried out during the laboratory test.

Towing Test				
Towing speed (kn)	**Force direction º**	**RESULTS**	**Column ballast (tn) C1, C2, C3**	**CONFIGURATION 4 (Totally Open) Orifice R1, R2, R3, R4, R5 (m)**
2	0	**towing resistance and drag coeff**	95, 95, 95	0,033 / 0,033 / 0,033 / 0,033 / 0,033
4	0		95, 95, 95	0,033 / 0,033 / 0,033 / 0,033 / 0,033
6	0		95, 95, 95	0,033 / 0,033 / 0,033 / 0,033 / 0,033
8	0		95, 95, 95	0,033 / 0,033 / 0,033 / 0,033 / 0,033

Table 25. Towing Test.

4.2.1.5 *Static offset tests*

Based on the moored structure, the stiffness of the mooring system will be assessed as well as the pretension of the mooring system is well represented in the laboratory. Two configurations and 4 displacements will be tested:

- Surge
- Sway

The configuration employ to execute the mooring stiffness test will be ***Configuration 4 (Chambers totally open).***

The Table 26 shows the mooring stiffness test to do during the laboratory test.

MOORING STIFFNESS TEST				
DOF	**Force direction º**	**RESULTS**	**Column ballast C1, C2, C3**	**CONFIGURATION 4 (Totally Open) Orifice R1, R2, R3, R4, R5 (m)**
Surge	0	restoring force of the moored model	95, 95, 95	0,033 / 0,033 / 0,033 / 0,033 / 0,033
Sway	90		95, 95, 95	0,033 / 0,033 / 0,033 / 0,033 / 0,033

Table 26. Static Offset test.

4.2.1.6 *Decay tests*

Decay tests are used on floating structures in order to determine the natural periods and the hydrodynamic damping of the system. They will be done both with and without the mooring installed. Therefore, the influence of the anchoring system on the natural period of the platform as well as the damping of the movement will be assessed.

The configurations used to execute the decay test will be ***Configuration 4 (Chambers totally open) and Configuration 1 (Chambers totally closed)***

The Table 27 shows the decay test without mooring system to achieve during the laboratory test.

Decay Test without Mooring System			
D.O.F.	**RESULTS**	**Column ballast C1, C2, C3**	**Orifice R1, R2, R3, R4, R5 (m)**
Configuration 1			
Heave	natural periods and damping coeff of the free model	95, 95, 95	closed/ closed/ closed/ closed/ closed
Pitch		95, 95, 95	closed/ closed/ closed/ closed/ closed
Configuration 3			
Heave	natural periods and damping coeff of the free model	95, 95, 95	0,033 / 0,033 / 0,033 / 0,033 / 0,033
Pitch		95, 95, 95	0,033 / 0,033 / 0,033 / 0,033 / 0,033

Table 27. Decay test without mooring system.

The Table 28 shows the decay test with mooring system to achieve during the laboratory test.

Decay Test with Mooring System			
D.O.F.	**RESULTS**	**Column ballast C1, C2, C3**	**Orifice R1, R2, R3, R4, R5 (m)**
Configuration 1			
Surge	natural periods and damping coeff of the free model	95, 95, 95	closed/ closed/ closed/ closed/ closed
Sway		95, 95, 95	closed/ closed/ closed/ closed/ closed
Heave		95, 95, 95	closed/ closed/ closed/ closed/ closed
Roll		95, 95, 95	closed/ closed/ closed/ closed/ closed
Pitch		95, 95, 95	closed/ closed/ closed/ closed/ closed
Yaw		95, 95, 95	closed/ closed/ closed/ closed/ closed
Configuration 3			
Surge	natural periods and damping coeff of the free model	95, 95, 95	0,033 / 0,033 / 0,033 / 0,033 / 0,033
Sway		95, 95, 95	0,033 / 0,033 / 0,033 / 0,033 / 0,033
Heave		95, 95, 95	0,033 / 0,033 / 0,033 / 0,033 / 0,033
Roll		95, 95, 95	0,033 / 0,033 / 0,033 / 0,033 / 0,033
Pitch		95, 95, 95	0,033 / 0,033 / 0,033 / 0,033 / 0,033
Yaw		95, 95, 95	0,033 / 0,033 / 0,033 / 0,033 / 0,033

Table 28. Decay test with mooring system.

4.2.2 Regular wave test

The MUP will be tested with regular waves. The objective of these tests is to determine the response of the structure against the waves (RAO (response amplitude operator) functions), and check the natural frequencies of the structure.

At least 9 frequencies will be tested. The wave height considered will be 3 m in a prototype scale. Wave frequency range will be performed covering the ocean natural frequencies.

Two different regular waves will be generated:

1. Regular wave without wind.
2. Regular Wave with wind.

Regular wave test without wind will be generated for the four configurations describe in the previous paragraphs, however regular wave with wind will be realized for the configuration 1 (chambers opening closed) and configuration 4 (chambers opening totally open).

The duration of regular test will be formed almost by 100 waves or until the system formed for the platform and mooring system will have steady behavior.

Table 29-Table 32 show the Regular wave tests carried out in full scale with and without wind for all configurations.

PaCOS - Regular Wave - Configuration 1 - OWC Totally Closed

Wind	Waves		Depth (m)	Wave Espectrum	Escale factor	Column ballast (tn) C1, C2, C3	CONFIGURATION 1 (Close) Orifice R1, R2, R3, R4, R5 (m)
Speed (m/s)	Height (m)	Period (s)					
11,5	3	8	105	REG	1/35	285, 0, 0	closed/ closed/ closed/ closed/ closed
11,5	3	12	105	REG	1/35	285, 0, 0	closed/ closed/ closed/ closed/ closed
11,5	3	14	105	REG	1/35	285, 0, 0	closed/ closed/ closed/ closed/ closed
11,5	3	18	105	REG	1/35	285, 0, 0	closed/ closed/ closed/ closed/ closed
11,5	3	22	105	REG	1/35	285, 0, 0	closed/ closed/ closed/ closed/ closed
11,5	3	25	105	REG	1/35	285, 0, 0	closed/ closed/ closed/ closed/ closed
0,0	3	8	105	REG	1/35	95, 95, 95	closed/ closed/ closed/ closed/ closed
0,0	3	10	105	REG	1/35	95, 95, 95	closed/ closed/ closed/ closed/ closed
0,0	3	12	105	REG	1/35	95, 95, 95	closed/ closed/ closed/ closed/ closed
0,0	3	14	105	REG	1/35	95, 95, 95	closed/ closed/ closed/ closed/ closed
0,0	3	16	105	REG	1/35	95, 95, 95	closed/ closed/ closed/ closed/ closed
0,0	3	18	105	REG	1/35	95, 95, 95	closed/ closed/ closed/ closed/ closed
0,0	3	20	105	REG	1/35	95, 95, 95	closed/ closed/ closed/ closed/ closed
0,0	3	22	105	REG	1/35	95, 95, 95	closed/ closed/ closed/ closed/ closed
0,0	3	25	105	REG	1/35	95, 95, 95	closed/ closed/ closed/ closed/ closed

Table 29. Configuration 1: Regular wave test.

PaCOS - Regular Wave - Configuration 2 - OWC Minimum Opening

Wind	Waves		Depth (m)	Wave Espectrum	Escale factor	Column ballast (tn) C1, C2, C3	CONFIGURATION 2 (Minimun Opening) Orifice R1, R2, R3, R4, R5 (m)
Speed (m/s)	Height (m)	Period (s)					
0,0	3	8	105	REG	1/35	95, 95, 95	0,02/ closed/ closed/ closed/ closed
0,0	3	10	105	REG	1/35	95, 95, 95	0,02/ closed/ closed/ closed/ closed
0,0	3	12	105	REG	1/35	95, 95, 95	0,02/ closed/ closed/ closed/ closed
0,0	3	14	105	REG	1/35	95, 95, 95	0,02/ closed/ closed/ closed/ closed
0,0	3	16	105	REG	1/35	95, 95, 95	0,02/ closed/ closed/ closed/ closed
0,0	3	18	105	REG	1/35	95, 95, 95	0,02/ closed/ closed/ closed/ closed
0,0	3	20	105	REG	1/35	95, 95, 95	0,02/ closed/ closed/ closed/ closed
0,0	3	22	105	REG	1/35	95, 95, 95	0,02/ closed/ closed/ closed/ closed
0,0	3	25	105	REG	1/35	95, 95, 95	0,02/ closed/ closed/ closed/ closed

Table 30. Configuration 2: Regular wave test.

PaCOS - Regular Wave - Configuration 3 - OWC Intermediate Opening							
Wind Speed (m/s)	Waves		Depth (m)	Wave Espectrum	Escale factor	Column ballast (tn) C1, C2, C3	CONFIGURATION 3 (Intermediate Opening) Orifice R1, R2, R3, R4, R5 (m)
	Height (m)	Period (s)					
0,0	3	8	105	REG	1/35	95, 95, 95	0,033/ closed/ closed/ closed/ closed
0,0	3	10	105	REG	1/35	95, 95, 95	0,033/ closed/ closed/ closed/ closed
0,0	3	12	105	REG	1/35	95, 95, 95	0,033/ closed/ closed/ closed/ closed
0,0	3	14	105	REG	1/35	95, 95, 95	0,033/ closed/ closed/ closed/ closed
0,0	3	16	105	REG	1/35	95, 95, 95	0,033/ closed/ closed/ closed/ closed
0,0	3	18	105	REG	1/35	95, 95, 95	0,033/ closed/ closed/ closed/ closed
0,0	3	20	105	REG	1/35	95, 95, 95	0,033/ closed/ closed/ closed/ closed
0,0	3	22	105	REG	1/35	95, 95, 95	0,033/ closed/ closed/ closed/ closed
0,0	3	25	105	REG	1/35	95, 95, 95	0,033/ closed/ closed/ closed/ closed

Table 31. Configuration 3: Regular wave test.

PaCOS - Regular Wave - Configuration 4 - OWC Open							
Wind Speed (m/s)	Waves		Depth (m)	Wave Espectrum	Escale factor	Column ballast (tn) C1, C2, C3	CONFIGURATION 4 (Totally Open) Orifice R1, R2, R3, R4, R5 (m)
	Height (m)	Period (s)					
11,5	3	8	105	REG	1/35	285, 0, 0	0,033 / 0,033 / 0,033 / 0,033 / 0,033
11,5	3	12	105	REG	1/35	285, 0, 0	0,033 / 0,033 / 0,033 / 0,033 / 0,033
11,5	3	14	105	REG	1/35	285, 0, 0	0,033 / 0,033 / 0,033 / 0,033 / 0,033
11,5	3	18	105	REG	1/35	285, 0, 0	0,033 / 0,033 / 0,033 / 0,033 / 0,033
11,5	3	22	105	REG	1/35	285, 0, 0	0,033 / 0,033 / 0,033 / 0,033 / 0,033
11,5	3	25	105	REG	1/35	285, 0, 0	0,033 / 0,033 / 0,033 / 0,033 / 0,033
0,0	3	8	105	REG	1/35	95, 95, 95	0,033 / 0,033 / 0,033 / 0,033 / 0,033
0,0	3	10	105	REG	1/35	95, 95, 95	0,033 / 0,033 / 0,033 / 0,033 / 0,033
0,0	3	12	105	REG	1/35	95, 95, 95	0,033 / 0,033 / 0,033 / 0,033 / 0,033
0,0	3	14	105	REG	1/35	95, 95, 95	0,033 / 0,033 / 0,033 / 0,033 / 0,033
0,0	3	16	105	REG	1/35	95, 95, 95	0,033 / 0,033 / 0,033 / 0,033 / 0,033
0,0	3	18	105	REG	1/35	95, 95, 95	0,033 / 0,033 / 0,033 / 0,033 / 0,033
0,0	3	20	105	REG	1/35	95, 95, 95	0,033 / 0,033 / 0,033 / 0,033 / 0,033
0,0	3	22	105	REG	1/35	95, 95, 95	0,033 / 0,033 / 0,033 / 0,033 / 0,033
0,0	3	25	105	REG	1/35	95, 95, 95	0,033 / 0,033 / 0,033 / 0,033 / 0,033

Table 32. Configuration 4: Regular wave test.

4.2.3 Irregular wave test

Tests with irregular wave have been considered. Inside this group, different irregular test will be realized combined irregular wave, wind and current. Irregular test have been divided in different groups. The classification of irregular tests are summarizes next:

1. Irregular Wave Test (only irregular waves)
2. Irregular Wave + Current Test
3. Operational Sea State (Irregular Wave + Wind or Irregular Wave + Wind +Current)
4. Survival Sea State (Irregular Wave + Wind +Current)

The duration of each Irregular Test will ensure a minimum of 500 waves in order to guaranty the complete development of sea state generated.

4.2.3.1 Irregular Wave Test (only waves)

The main goal of these tests is to determine the response of the structure subject to irregular waves, that could produce 2nd order excitation forces due to the wave groups that are not produced by the regular waves. The information gathered in these tests will contribute to the database for calibration and validation of the numerical models.

These test will be done for the configurations 2, 3 and 4.

Table 33 to Table 35 show the irregular wave test (only waves) in full scale for all configurations.

PaCOS - Irregular Wave Test - Configuration 4 - OWC Open									
Wind	**Waves**		**γ**	**Current**	**Depth (m)**	**Wave Espectrum**	**Escale factor**	**Column ballast (tn) C1, C2, C3**	**CONFIGURATION 4 (Totally Open) Orifice R1, R2, R3, R4, R5 (m)**
Speed (m/s)	**Hs (m)**	**Tp (s)**		**Speed (m/s)**					
0,0	3	7,79	1,70	0,00	105	JW	1/35	95, 95, 95	0,033 / 0,033 / 0,033 / 0,033 / 0,033
0,0	3	10,39	2,60	0,00	105	JW	1/35	95, 95, 95	0,033 / 0,033 / 0,033 / 0,033 / 0,033
0,0	3	12,99	2,40	0,00	105	JW	1/35	95, 95, 95	0,033 / 0,033 / 0,033 / 0,033 / 0,033
0,0	3	7,79	3,30	0,00	105	JW	1/35	95, 95, 95	0,033 / 0,033 / 0,033 / 0,033 / 0,033
0,0	3	10,39	3,30	0,00	105	JW	1/35	95, 95, 95	0,033 / 0,033 / 0,033 / 0,033 / 0,033
0,0	3	12,99	3,30	0,00	105	JW	1/35	95, 95, 95	0,033 / 0,033 / 0,033 / 0,033 / 0,033
0,0	3	16,00	3,30	0,00	105	JW	1/35	95, 95, 95	0,033 / 0,033 / 0,033 / 0,033 / 0,033
0,0	3	19,00	3,30	0,00	105	JW	1/35	95, 95, 95	0,033 / 0,033 / 0,033 / 0,033 / 0,033
0,0	3	22,00	3,30	0,00	105	JW	1/35	95, 95, 95	0,033 / 0,033 / 0,033 / 0,033 / 0,033
0,0	3	25,00	3,30	0,00	105	JW	1/35	95, 95, 95	0,033 / 0,033 / 0,033 / 0,033 / 0,033

Table 33. Configuration 1: Irregular wave test (only waves).

PaCOS - Irregular Wave Test- Configuration 2 - OWC Minimum Opening									
Wind	**Waves**		**γ**	**Current**	**Depth (m)**	**Wave Espectrum**	**Escale factor**	**Column ballast (tn) C1, C2, C3**	**CONFIGURATION 2 (Minimun Opening) Orifice R1, R2, R3, R4, R5 (m)**
Speed (m/s)	**Hs (m)**	**Tp (s)**		**Speed (m/s)**					
0,0	3	7,79	1,70	0,00	105	JW	1/35	95, 95, 95	0,02/ closed/ closed/ closed/ closed
0,0	3	10,39	2,60	0,00	105	JW	1/35	95, 95, 95	0,02/ closed/ closed/ closed/ closed
0,0	3	12,99	2,40	0,00	105	JW	1/35	95, 95, 95	0,02/ closed/ closed/ closed/ closed

Table 34. Configuration 2: Irregular wave test (only waves).

PaCOS - Irregular Wave - Configuration 3 - OWC Intermediate Opening									
Wind	**Waves**		**γ**	**Current**	**Depth (m)**	**Wave Espectrum**	**Escale factor**	**Column ballast (tn) C1, C2, C3**	**CONFIGURATION 3 (Totally Open) Orifice R1, R2, R3, R4, R5 (m)**
Speed (m/s)	**Hs (m)**	**Tp (s)**		**Speed (m/s)**					
0,0	3	7,79	1,70	0,00	105	JW	1/35	95, 95, 95	0,033/ closed/ closed/ closed/ closed
0,0	3	10,39	2,60	0,00	105	JW	1/35	95, 95, 95	0,033/ closed/ closed/ closed/ closed
0,0	3	12,99	2,40	0,00	105	JW	1/35	95, 95, 95	0,033/ closed/ closed/ closed/ closed

Table 35. Configuration 3: Irregular wave test (only waves).

4.2.3.2 Irregular Waves + Current

This kind of test, irregular waves + current, only will be done for the configuration 4 (chambers layout opening totally open). Irregular waves + current test will be used to compare the influence of the current over the multi-use platform, doing a comparison between results obtained in these test with the results obtained in the test with only irregular waves.

The Table 36 shows the irregular wave test with currents in full scale for all configurations.

PaCOS - Irregular Wave + Current Test - Configuration 4 - OWC Open									
Wind	Waves		γ	Current	Depth (m)	Wave Espectrum	Escale factor	Column ballast (tn) C1, C2, C3	CONFIGURATION 4 (Totally Open) Orifice R1, R2, R3, R4, R5 (m)
Speed (m/s)	Hs (m)	Tp (s)		Speed (m/s)					
0,0	3	7,79	1,70	0,90	105	JW	1/35	95, 95, 95	0,033 / 0,033 / 0,033 / 0,033 / 0,033
0,0	3	10,39	2,60	0,90	105	JW	1/35	95, 95, 95	0,033 / 0,033 / 0,033 / 0,033 / 0,033
0,0	3	12,99	2,40	0,90	105	JW	1/35	95, 95, 95	0,033 / 0,033 / 0,033 / 0,033 / 0,033

Table 36. Configuration 4: Irregular wave test (waves + currents).

4.2.3.3 Operational Sea State (Wave + Wind + Current)

These conditions correspond to real sea state when the wind turbine and oscillating water column are in operation.

Operational sea states will be executed for the configuration 2 (minimum chambers opening) and configuration 4 (chambers opening totally open).

The test variables are:

- Significant wave height, H_s ($H_s \cong H_{mo}$)
- Peak period, T_p
- Mean direction of wave propagation, θ_o
- Hourly average wind speed, V_v
- Hourly Wind direction, θ_v
- Current Velocity

Finally Table 37 and Table 38 show the operational sea state to generate during the laboratory test.

PaCOS - Operational Sea State- Configuration 4 - OWC Open									
Wind	Waves		γ	Current	Depth (m)	Wave Espectrum	Escale factor	Column ballast (tn) C1, C2, C3	CONFIGURATION 4 (Totally Open) Orifice R1, R2, R3, R4, R5 (m)
Speed (m/s)	Hs (m)	Tp (s)		Speed (m/s)					
6,0	1,88	9,15	2,30	0,00	105	JW	1/35	175, 55, 55	0,033 / 0,033 / 0,033 / 0,033 / 0,033
11,5	1,88	9,15	2,30	0,00	105	JW	1/35	285, 0, 0	0,033 / 0,033 / 0,033 / 0,033 / 0,033
16,0	1,88	9,15	2,30	0,00	105	JW	1/35	215, 35, 35	0,033 / 0,033 / 0,033 / 0,033 / 0,033
6,0	3	10,39	2,60	0,00	105	JW	1/35	175, 55, 55	0,033 / 0,033 / 0,033 / 0,033 / 0,033
11,5	3	10,39	2,60	0,00	105	JW	1/35	285, 0, 0	0,033 / 0,033 / 0,033 / 0,033 / 0,033
16,0	3	10,39	2,60	0,00	105	JW	1/35	215, 35, 35	0,033 / 0,033 / 0,033 / 0,033 / 0,033
6,0	5	11,92	2,30	0,90	105	JW	1/35	175, 55, 55	0,033 / 0,033 / 0,033 / 0,033 / 0,033
11,5	5	11,92	2,30	0,90	105	JW	1/35	285, 0, 0	0,033 / 0,033 / 0,033 / 0,033 / 0,033
16,0	5	11,92	2,30	0,90	105	JW	1/35	215, 35, 35	0,033 / 0,033 / 0,033 / 0,033 / 0,033

Table 37. Configuration 4. Operational sea state.

PaCOS - Operational Sea State- Configuration 2 - OWC Minimum Opening									
Wind	Waves		γ	Current	Depth (m)	Wave Espectrum	Escale factor	Column ballast (tn) C1, C2, C3	CONFIGURATION 2 (Minimun Opening) Orifice R1, R2, R3, R4, R5 (m)
Speed (m/s)	Hs (m)	Tp (s)		Speed (m/s)					
6,0	1,88	9,15	2,30	0,00	105	JW	1/35	175, 55, 55	0,02/ closed/ closed/ closed/ closed
11,5	1,88	9,15	2,30	0,00	105	JW	1/35	285, 0, 0	0,02/ closed/ closed/ closed/ closed
16,0	1,88	9,15	2,30	0,00	105	JW	1/35	215, 35, 35	0,02/ closed/ closed/ closed/ closed
6,0	3	10,39	2,60	0,00	105	JW	1/35	175, 55, 55	0,02/ closed/ closed/ closed/ closed
11,5	3	10,39	2,60	0,00	105	JW	1/35	285, 0, 0	0,02/ closed/ closed/ closed/ closed
16,0	3	10,39	2,60	0,00	105	JW	1/35	215, 35, 35	0,02/ closed/ closed/ closed/ closed
6,0	5	11,92	2,30	0,00	105	JW	1/35	175, 55, 55	0,02/ closed/ closed/ closed/ closed
11,5	5	11,92	2,30	0,00	105	JW	1/35	285, 0, 0	0,02/ closed/ closed/ closed/ closed
16,0	5	11,92	2,30	0,00	105	JW	1/35	215, 35, 35	0,02/ closed/ closed/ closed/ closed

Table 38. Configuration 2. Operational sea state.

4.2.3.4 Survival Sea State:

The survival conditions correspond to a fully developed SEA. Survival sea state test are used to determine the no-linear behavior of the floating platform, moreover extreme conditions also will be used to determine the feasibility of the accelerations at the nacelle, loads at the mooring system and platform movements.

The test variables are:

- Significant wave height, Hs ($H_s \cong H_{mo}$)
- Peak period, T_p
- Average direction of wave propagation, θ_o
- Hourly average wind speed, V_v
- Mean hourly wind direction, θ_v
- Current Velocity

Survival sea state only will be generated for configuration 4 (Chambers totally open).

The Table 39 shows the survival sea states.

PaCOS - Survival Sea State- Configuration 4 - OWC Open									
Wind	Waves		γ	Current	Depth (m)	Wave Espectrum	Escale factor	Column ballast (tn) C1, C2, C3	CONFIGURATION 4 (Totally Open) Orifice R1, R2, R3, R4, R5 (m)
Speed (m/s)	Hs (m)	Tp (s)		Speed (m/s)					
32,0	10,78	11,00	2,10	0,90	105	JW	1/35	125, 80, 80	0,033 / 0,033 / 0,033 / 0,033 / 0,033
32,0	10,78	14,67	2,10	0,90	105	JW	1/35	125, 80, 80	0,033 / 0,033 / 0,033 / 0,033 / 0,033
32,0	10,78	18,34	2,10	0,90	105	JW	1/35	125, 80, 80	0,033 / 0,033 / 0,033 / 0,033 / 0,033

Table 39. Configuration 4. Survival sea state.

4.3 Instrumentation of a physical model of the PTA

The instrumentation that will be installed on the model will be composed by:

- 6DOF optical tracking motions (by Qualisys) at various points of the platform and tower
- Load cell (6DOF) at the junction between the tower and the nacelle
- Axial load cells in each fairlead of the mooring system.
- Free surface sensors to monitor the incident and reflected wave. An additional sensor for measuring the wave height of the structure.

- ADV sensor to measure current velocity.
- Pressure Sensor to measure the pressure in the OWC.

Most of the instrumentation installed on the model will be cordless type if is it possible, to avoid interference from the cables with the movements and load distribution of the platform.

4.4 Wave generation diagram

The CCOB wave generation diagram is shown in Figure 100.

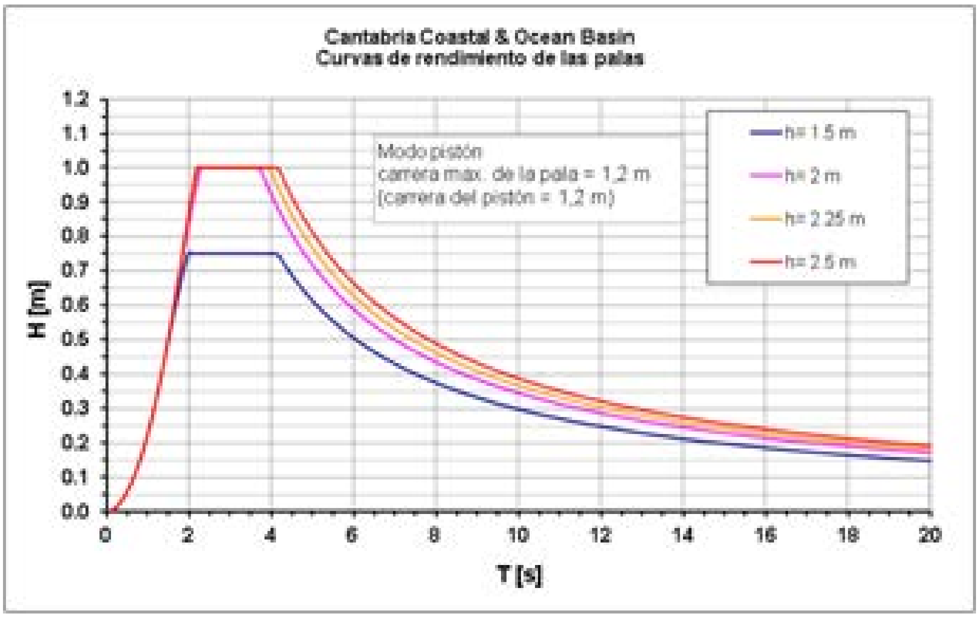


Figure 100. CCOB wave generation diagram.

5 WORK PLAN

A summary of the tests can be found on Deliverable 7.3.

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Grant Agreement no.: 288710
Start date of project*: 01 Jan 2012 - Duration: 48 month*

Integration of energy converters in multi-use offshore platforms

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Table of contents

1 Introduction

The purpose of this document is to provide an overview of offshore grid connection technology: the topic has been tackled with a general approach spacing from oil & gas to renewable energy sectors as main applications in offshore electricity transmission and distribution technologies.

This reports outlines the current state of art of the most important technology groups required for the realization of offshore energy farms that have been identified in energy generation, collection/distribution system, transmission system, connection to shore.
Indications of costs and relevant standards are given in the final part of the report.

2 Offshore Power Generation and utilization/general context

2.1 Introduction

Offshore oil & gas sector is a well established technological segment and is of particular interest for renewable offshore projects especially, but not limited to, for what concern:

- power supply of offshore platforms,
- support structures for offshore platforms,
- engineering solutions and components relevant to subsea production systems,
- installation techniques and O&M practices.

Production platforms have a large power demand in order to cover a wide range of activities related to hydrocarbons extractions: energy needs vary according to operation conditions and site of location and are in many cases supplied by locally produced gas turbines at quite low efficiencies, even if this solution is very expensive. If the power requested increases, it is viable to connect the platform to the onshore grid via an electrical connection as the Norwegian gas platform “Troll A” where electric power supply is assured by an HVDC link.

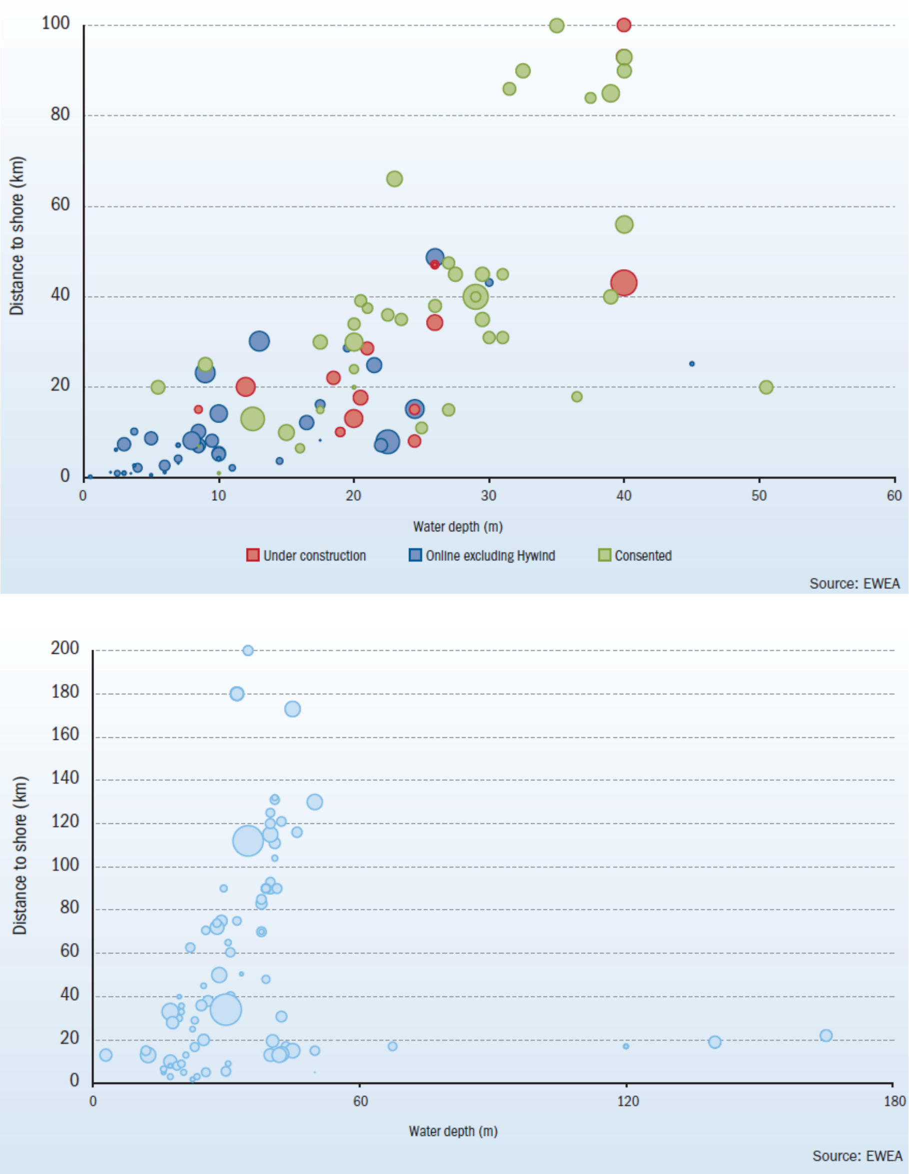
Offshore hydrocarbons extraction activities has seen a huge variety of substructure supporting drilling and processing facilities, in order to reach deeper waters and sustain heavy equipment.

In the last years a lot of activities has moved directly on the seabed, giving a strong contribution to the development and establishment of the subsea engineering sector that can be used as an important reference for the deployment of marine energy.

Offshore generation can be divided in wind, wave and tidal farms: the last two are relatively new so there are only some demonstrative small power plants or single device installations to take as reference and analyze.

Offshore Wind farms are not new to the electricity market specially in North Europe. The first offshore wind farm was inaugurated in 1991, 2.5 km off the Danish coast at Vindeby [1]: it was characterized by a total capacity of 4.95 MW and featured by eleven 450 kW turbines. By the end of 2012, 1662 turbines were installed and grid connected, for a total of 4,995 MW in 55 wind farms in ten European countries [2].

The majority of wind farms that are already operating are concentrated up to 20 km from shore and in water depths of up 20 m, while a large amount of consented or under construction are located in depths up to 60 m and up to 60 km from shore. Wind farms placed more than 60 km far from shore will ideally be connected to offshore supernodes for water depths not exceeding 60m, while for water depth bigger than 60m wind farms planned consists of new concept using floating platform technologies.



Source: EWEA

Source: EWEA

Figure 1 - Distance and depth of online, consented under construction offshore windfarms (up) and planned offshore windfarms (down) [1]. The size of each circle refers to the capacity of each wind farm.

An offshore wind farm consists of wind turbine generators (WTG) connected by a grid of submarine cables that collect the power generated and bring it to shore. Generally medium voltage (MV) cables connects the WTGs and then the wind farm to the mainland grid for distances up to about 10 km and power exported of the order of 30-40MW. For higher distances to shore and/or large output power high voltage connection (HV) is preferred and sometimes of the direct current type (HVDC): in these cases converter stations are required, respectively MV/HV substations located offshore in the first, AC/DC offshore and DC/AC, generally onshore substations, in the latter.

For distances exceeding a few kilometers, HVAC solution is often chosen for the fact that it allows the use of small number of HV cables, typically in the range of 120 to 150kV: this represents a cost advantage even if implying an offshore substation. Equipment onboard offshore substations is similar to that of onshore substation except for the fact that there is the need for a specific environmental protection. Since a failure in the offshore substation may bring to a loss in energy production, particular designs solutions offering redundancy (two transformer, two HVAC cables) have been recently developed. HVDC is representing the choice of German Transmission System Operator for the connection of offshore wind farms clusters with a total capacity of 800-900 MW.

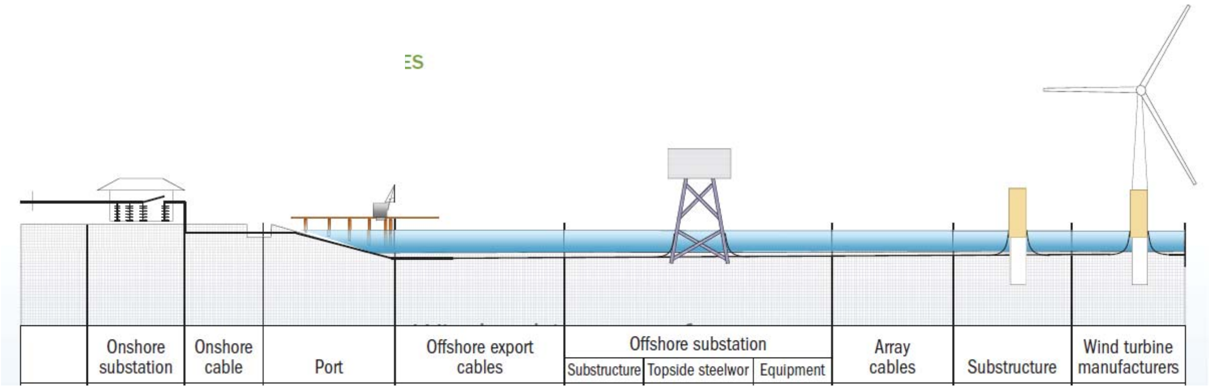


Figure 2 – Example of grid connection elements of an offshore windfarm [1].

Offshore wind technology represents an evolution of onshore technical solutions mainly obtained moving ashore land-based equipment: obviously marine energy development is much complex since it has not an onshore history and then an onshore experience to refer to and to adapt to applications in the sea.

As a consequence the sizes of marine plants currently installed are very small. Among these plants only a poor number is constituted by grid-connected devices and this means that no standard collection and connection configuration and equipment exist; relevant choices have been generally made on a case by case analysis, mainly both "site and device specific". In addition is to be highlighted that such technical solutions have been often dictated by financial and economic constraints that may be no longer valid if referred to permanent and big installations instead of a single device installation.

Experiences made until now in the marine energy technology have shown the importance of extensive open sea testing operation to assess efficiency and profitability of energy converters and to identify optimization and improvement factors. In this context many testing facilities already in operation or under construction provide the possibility to connect energy converters to the main grid (almost distribution grid) via a set of equipment and structure especially designed for this purpose. Even if these connection solutions are not expressly designed thinking at large scale applications they could represent first examples to refer to.

The European Marine Energy Centre (EMEC), Orkney Islands in Scotland, is the first open sea testing facility (in operation since 2003) that includes installations for wave and tidal energy converters. The wave testing site is located near Stromness, in an area located between 1 and 2 kilometres from the coast and at a depth of up to 70m: it includes 5 berths of 2,2 MW capacity, each directly connected to an onshore substation by a 11kV cable. There is also another berth for shallow water installation. The connection to the grid is obtained with a secondary substation (11-33kV) placed close to the coast and has power maximum feeding of 7 MW. The tidal testing site is located close to Eday, in an area of 2km times 3,5 km, at water depth between 12 and 50m. It include 8 berths of 5 MW each directly connected via a 11kV cable to a substation, and then the connection to the grid is obtained with a secondary substation (from 11 to 15 kV) close to the coast and has a power maximum feeding of 4MW [3].

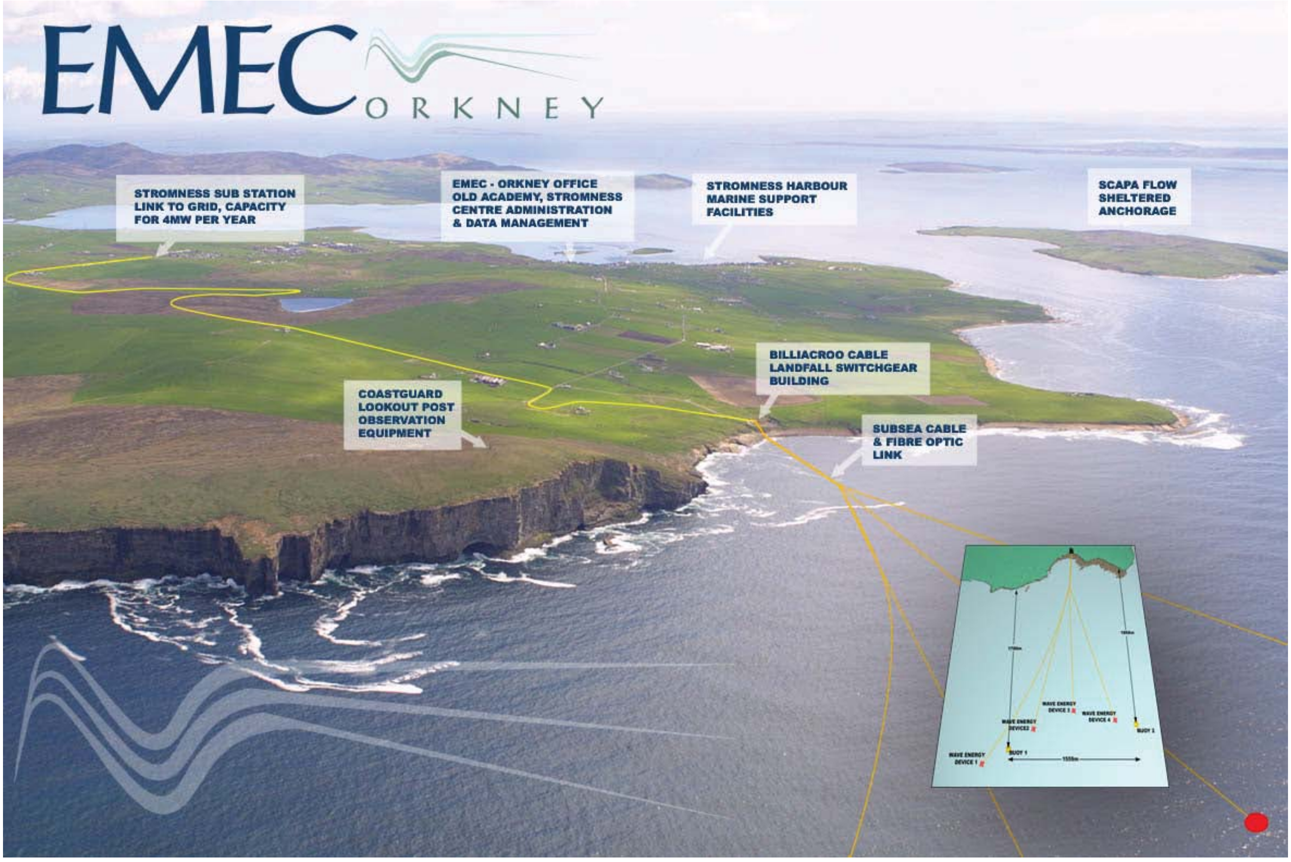


Figure 3 - EMEC test site [3].

The Wave Hub is a grid-connected offshore facility in South West England, characterized by 8 sq km of sea bed connected to the grid by a 11/33kv subsea cable that provides shared offshore infrastructure for the demonstration and proving of arrays of wave energy converters. It consists of an electrical hub on the seabed 16 kilometres off the north coast of Cornwall in South West England to which wave energy devices can be connected. Four separate berths are available to lease, each with a capacity of 4-5MW. Wave Hub can readily be upgraded for up to 50MW of generating capacity in the future once suitable components for operating the cable at 33kV have been developed [4].

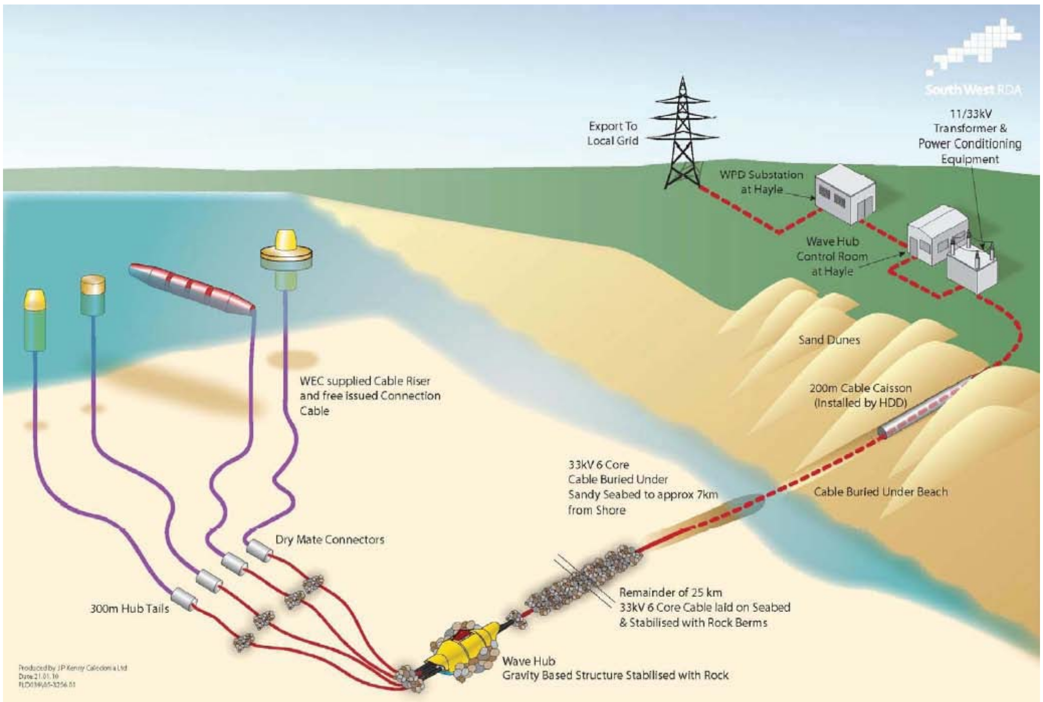


Figure 4 - Schematic of wave hub [4].

The Biscay Marine Energy Platform (BIMEP) is an open sea test infrastructure for testing full-scale prototype wave energy converters as single devices or arrays in order to assess and monitor performance. It is located off Biscay coast in the Basque Country (Spain) , at a water depth between 50-90m: it includes 4 test berths of 13 kV and 5 MW where four power subsea cables connect the WECs to an onshore substation (13/132 kV) where power is delivered to the grid [5].

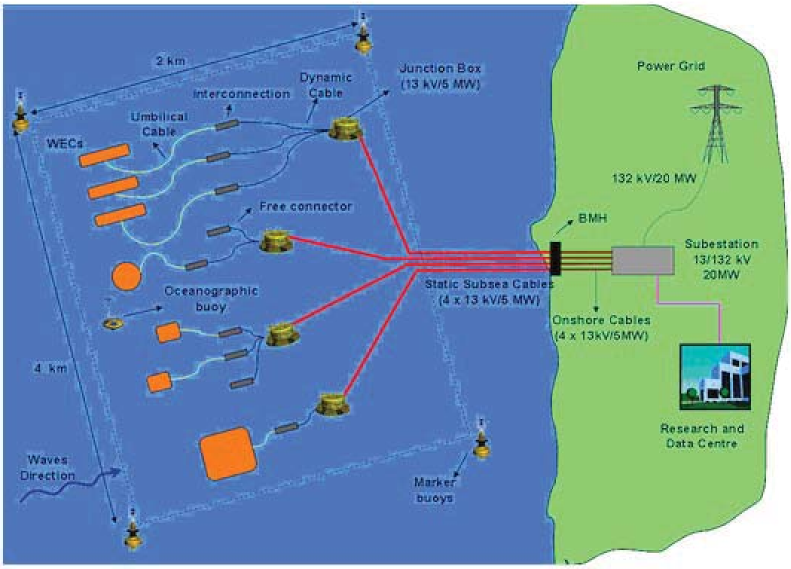


Figure 5 - Architecture and main components of BIMEP [5].

In the small size applications like the ones described above a simple electrical transmission system constituted by a separate connection between each marine energy device and the onshore substation is used.

Figure 6 - Basic concept of transmission system for small marine farms [6].

For larger-scale farms, in which losses in cables become important it may be preferred to rise voltage transmission level and include an offshore substation, shared by different devices.
It’s highly probable that marine farms with several devices each characterized by a significant rated power will follow connection schemes already used in offshore wind farms following the successful solutions and the lessons learnt in this earlier offshore energy application field.

Generally, taking into account the two main parameters - power (generated or consumed) and transmission distance, two connection solutions are available for the connection to the grid of an offshore facility: alternating current (AC) and direct current (DC).
The AC solutions has lower costs for AC substations then DC solution, but for long distances the cost of cable become significant until it reaches a prohibitive value exceeding a certain distance: in fact long AC cables produce large amounts of capacitive reactive power that reduce power transmission capacity and needs to be balanced by inductive reactive power. With AC connection the offshore farm and the main grid are in synchronous operation and this means that all faults in the main grid directly affect the collecting AC grid offshore and vice versa: to mitigate this dynamic effect there is the need of a fast voltage control.
An advantage of the DC solution is given by the lower cost for cables and lower cable losses above a certain distance and thus compensates the high converter AC/DC substations costs. So for long distances DC becomes competitive both for the investments and for the operating costs.
In addition the DC transmission generally decouples power plant grid and the main grid, so this facilitates, in case of faults in the network, a fast return to pre-fault conditions. Using Voltage Source Converters (VSC) it is also possible to provide island operation and black start capability. All these features make DC solution more flexible in terms of capacity of supporting the main power system [7].

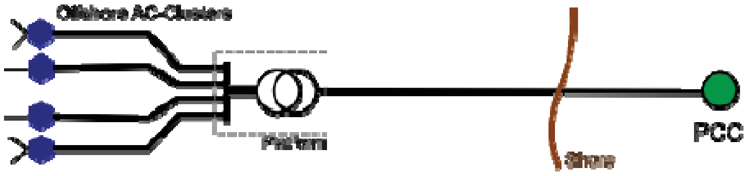


Figure 7 – Example of wind farm connection to grid via an HVAC link [6].

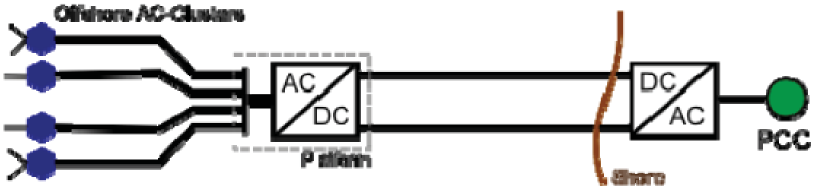


Figure 8 - Example of wind farm connection to grid via an HVDC link [6].

To connect distant autonomous grids submarine HVDC connection of even hundreds of kilometers have been used (NorNed, a pair of 580km cables).

Islands close to the mainland can be connected to onshore grid by MV (<52kV) submarine cables for power transmission levels in the range of 10-30MW and for length of 10-30km. For longer distances is preferred to step up voltage level and switch to HVDC technology [8].

2.2 Oil&Gas sector

The offshore oil and gas industry started in 1947 with the completion of a subsea well in the Gulf of Mexico: typically hydrocarbons are extracted from the wells and brought to the surface to a processing host facility above the ocean surface or to an onshore facility.

Offshore platforms are used to drill wells, to extract and process oil and natural gas and to store products before sending it ashore. Such platforms host all the facilities and equipment to perform the activities described above and sometimes to house the needed workforce.

Oil and gas production process includes wellhead, production manifold, production separator, glycol process to dry gas, gas compressors, water injection pumps, oil/gas export metering and main oil line pumps.

Depending on the site of extraction, in particular on size and water depth, platforms can be divided into different types, principally in fixed or bottom supported and floating [9, 10].

In the first category we can find:

- **artificial gravel islands**: they may be used in water depths of up to about 15 m and can support large drilling rigs and oil and gas production equipment. Many tons of gravel are placed on the seafloor to create the island. When production is completed, the islands may be left to erode naturally or dredged to a depth that allows for vessel navigation. Gravel islands typically must be strengthened with concrete, rock or steel sheet piles to resist the impact of ice.
- **Steel jacket:** Typical fixed steel platforms consisting of large pipe legs and a tubular steel cross bracing that form a “jacket.” The jacket is supported by piles driven into the seafloor to transmit wave, wind, current or ice forces into the ground. They support a deck that contains a drilling rig, the crew’s living quarters and production facilities. Jackets are usually used in shallow to medium water depths and are intended for long-term use. Steel jacket platforms can operate in up to about 500 m of water depth and withstand hurricanes and winter storms.
- **Gravity-based structures**: These platforms take advantage of their large size and heavy mass to support large facilities in water depths of up to about 500 m. They can be made of steel or concrete, and provide support for heavy drilling rigs and production equipment. They function similarly to gravel islands and jacket structures, but can be used in deeper water than gravel islands and can resist ice much better than jacket structures. They effectively act as steel or concrete islands. Steel GBS do not usually provide hydrocarbon storage capability. They are mainly installed by pulling them off the yard, by either wet-tow or/and dry-tow, and self-installing by controlled ballasting of the compartments with sea water. To position the GBS during installation, the GBS can be connected to either a transportation barge or any other barge (provided it is large enough to support the GBS) using strand jacks. The jacks shall be released gradually whilst the GBS is ballasted to ensure that the GBS does not sway too much from target location.

- **Other conventional fixed structure:** in addition to steel jacket there are also platforms built on concrete or concrete and steel legs anchored directly onto seabed, concrete caisson, floating steel and even floating concrete. Concrete caisson structures often have in-built oil storage in tanks below the sea surface and these tanks were often used as a flotation capability, allowing them to be built close to shore (e.g. Norwegian fjords) and then floated to their final position where they are sunk to the seabed.

To the second category belong:

- **Compliant Towers:** In deeper waters (over about 450m), small steady waves can start to cause fatigue on fixed platform structures. “Compliant Tower” platforms are typically used for operating in depths ranging about from 450 and 1000m. The platforms are slender and so flexible that they sway when hit with these small waves so they don’t experience the fatigue that a fixed platform would see in these great depths. The narrow, flexible towers have pile foundations and can support a conventional deck for drilling and production operations.
- **Tension Leg Plat forms (TLPs):** These floating platforms can support a drilling rig and production facilities. The TLPs are similar to fixed platforms except they use a floating hull tethered to the seafloor by a mooring system made of tension legs. These steel “tendons” limit vertical movements from wind and sea forces and keep the TLP in position. Many TLPs are built with a four-column design that supports the deck section: proprietary version includes Seastar and MOSES mini TLP. Below the water, a ring of pontoons connects the columns, much like a semi-submersible drilling vessel. TLPs can be used in up to 2000 m of water.
- **Semi-Submersibles:** A semi-submersible production platform consists of a deck supported by columns and pontoons of sufficient buoyancy. Similar to TLPs, semi-submersibles can support living quarters and production equipment. To keep the platform in position, the floating hull can use both a lateral mooring system of steel cables, chains, wire ropes and/or polyester ropes and dynamic positioning: the connection with subsea wells is assured by flowlines and flexible risers. Semi-submersible platforms can be moved from place to place; can be ballasted up or down by altering the amount of flooding in buoyancy tanks. The subsea wells are drilled by mobile offshore drilling units since typically there is not a drill rig on a semi-submersible production platform. These platforms can be used in water depths ranging from about 60 to 3000m.
- **Spars:** Much like the TLP, Spars are moored to the seafloor, but with a more conventional lateral mooring anchoring system instead of tension legs. By using chain jacks attached to the mooring system it is also capable of laterally displacements. There are three type on design: the "conventional" one-piece cylindrical hull, the "truss spar" where the midsection is composed of truss elements connecting the upper buoyant hull (called a hard tank) with the bottom soft tank containing permanent ballast, and the "cell spar" which is built from multiple vertical cylinders. About 90 percent of the structure is underwater, so it has great stability in very deep waters (up to about 3000m). They can support dry completion wells but are more often used with subsea wells.
- **FPSOs:** Floating production storage and offloading units (FPSOs) can operate in water depths up to 3000m and are best suited for milder climates or where there is limited pipeline systems to transport oil to shore. These generally ship-like vessels can process all of the oil or gas produced from a reservoir, separating the oil and gas and storing the oil until it can be offloaded to tankers for transportation. Subsea wells send production to the FPSO through lines called “risers,” which are flexible enough to resist the heaving motion of the vessel above. Designs vary to allow different capabilities; some may be able to store and

offload (FSO for example) or only to store (FSU: floating storage unit) but do not process hydrocarbons. Most vessels use mooring systems connected to a “turret.” The turret is mounted to the hull and allows the vessel to rotate freely. Called “weathervaning,” this action allows the vessel’s bow always to point into the winds and currents, minimizing the impact of those forces. The turret has wire rope and chain connection to several anchors (position mooring) or can be dynamically positioned using thruster (dynamically positioning). FPSOs are either modified existing tankers or can be newly constructed: a variation is constituted by the Sevan Marine design which, using a circular hull, offers the same profile to wind, wave and current regardless of direction and , not rotating, does not need a rotating turret.

- **Mobile Offshore Drilling Units:** Wells are drilled from mobile offshore drilling units (MODUs) when no platform exists. MODUs are used for exploration wells and subsea production wells. They support the drilling equipment and living quarters, but have no processing equipment and can be easily moved once the drilling is done. They can be jacked up above the sea using legs that can be lowered, much like jacks. They are designed to move from place to place, and then anchor themselves by deploying the legs to the ocean bottom using a rack and pinion gear system on each leg. They are typically used in water depths up to 400 feet (120 m), although some designs can go to 170 m depth.

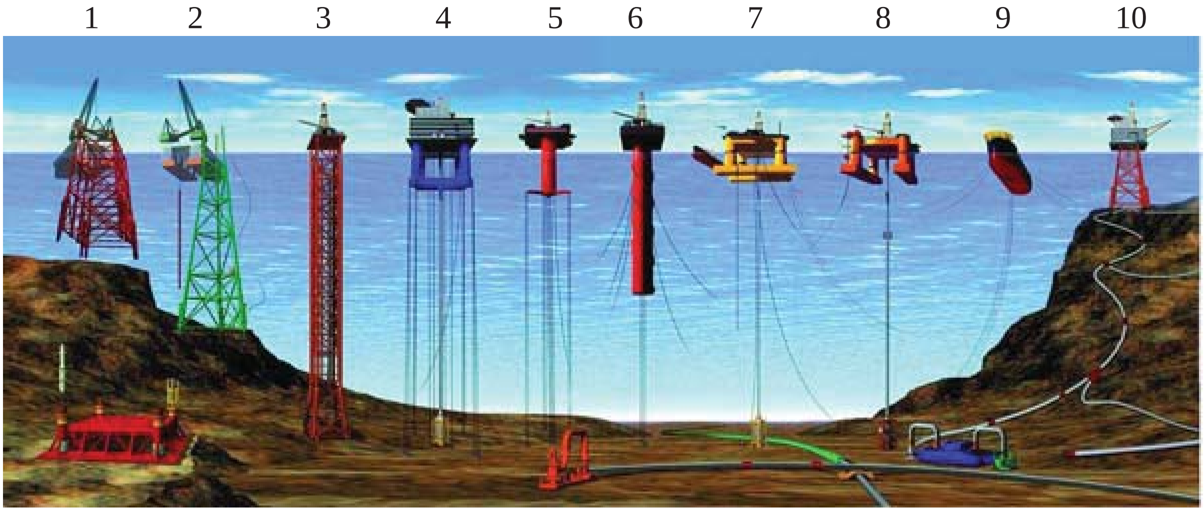


Figure 9 - 1,2) Conventional fixed platforms; 3) compliant tower; 4, 5) vertically moored tension leg and mini-tension leg platform; 6) Spar ; 7,8) Semi-submersibles ; 9) Floating production, storage, and offloading facility; 10) sub-sea completion and tie-back to host facility [10].

Special attention has to be given to Subsea Production Systems: these systems are composed of wells, manifolds, flowlines and umbilical cables lying directly on the seafloor. Such systems do not have the ability to drill but only to extract and transport oil or natural gas so they are drilled by MODUs and can be connected to other systems, like Spars, FPSOs, platforms or even onshore facilities up to about 250 km in horizontal distance.

2.2.1 Subsea production systems: history and evolution

In the 1970s, the wellhead production equipment and other components put inside a sealed chamber began to be placed directly on the seabed introducing the concept of subsea development and signing the begin of subsea engineering and of subsea production systems [11].

Subsea wells are placed in a subsea structure called template and from this they can be drilled and serviced remotely from the surface. The template has a slot for the mating of the wellhead and the hydraulic, electric, control signals and the outgoing pipeline. The subsea installation generally receive power from a hydraulic power unit located on the surface by means of umbilical connections: these are composite cables containing electrical power, control and communication signals, tension wires, hydraulic pipes and chemical injection connection. A control pod with oil protection and/or inert gas contains control electronics and allows equipment operation by hydraulic switches. More complex solutions contain subsea separation/stabilization and electrical multiphase pumping used in case of unstable gas/liquids flux to the surface. Figure 10 shows a typical subsea layout.

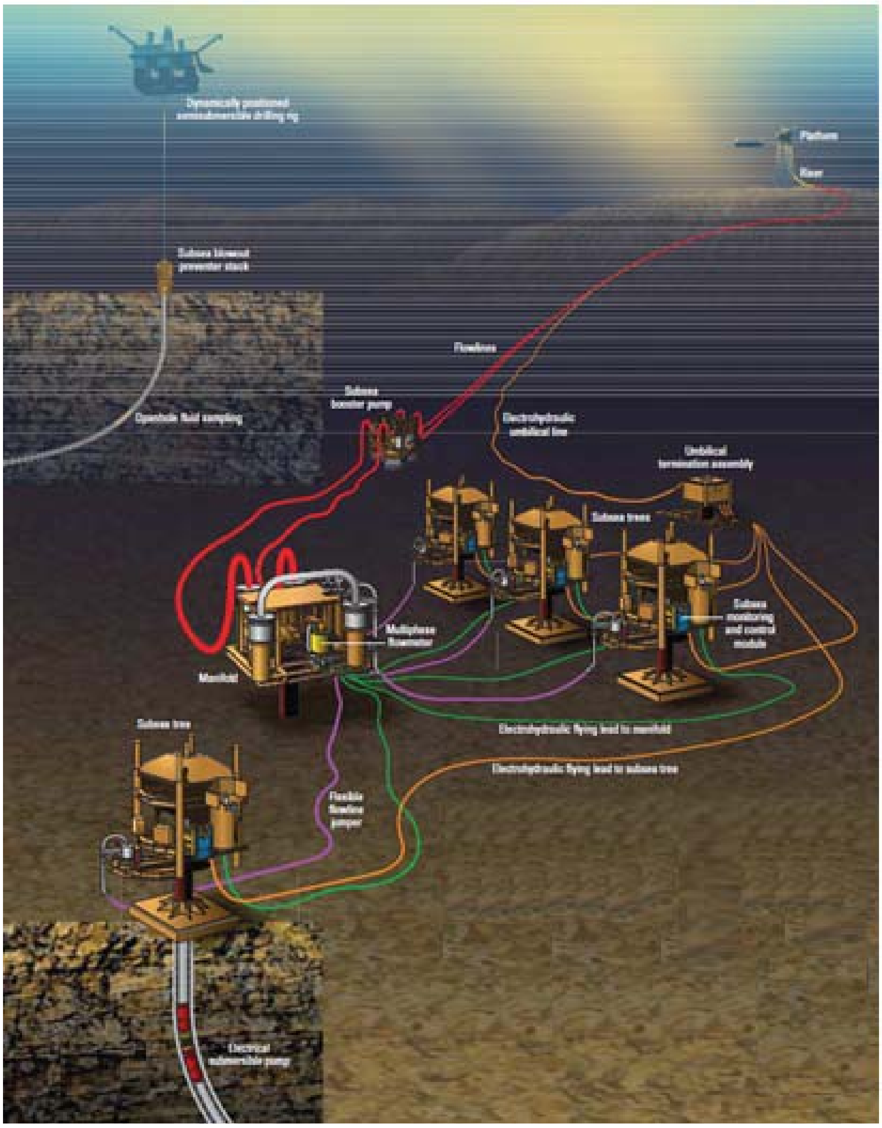


Figure 10 - Subsea layout [11].

Generally oil, gas and water flow from wellbore to subsea tree, then to jumper, manifold, flowline and finally to a riser that pipes it to the surface for processing: the production facility can be directly overhead (being a conventional , a spar or a floating platform) or many miles away, possibly even onshore.

Subsea trees are positioned on each completed well and contain pressure control valves and chemical injection ports. A flowline jumper carries produced fluids from each subsea tree to a manifold which commingles production from the wells before sending it through a flowline to a platform. A subsea booster pump sends produced fluid along the flowline and up to the riser to the platform’s production deck. Umbilical lines from the platform run back to a subsea umbilical termination assembly or unit before branching off to each wellhead and then to manifold: they supply electric and hydraulic power for wellhead and manifold control functions, and chemicals to suppress the formation of scale and hydrates in the production stream. Umbilical lines also carry bidirectional communications and control instructions between the platform, wellhead and downhole devices.

There are also technical solutions that use a subsea “all-electric” technology that consists of an electric-actuated subsea system that provide more rapid and accurate equipment performance and eliminate the need for larger and more expensive hydraulic and electro-hydraulic umbilicals.

An evolution of subsea production systems is constituted by putting production equipment on the seafloor rather than on a fixed or floating platform: this solution, known as subsea processing offers a less expensive solution for many offshore environments. It was originally conceived as a solution for extremely deepwater situations, but nowadays has become a viable solution for applications characterized by harsh conditions where processing equipment on the water's surface might be at risk.

Each item of process equipment can be powered from the surface or recent developments give the possibility to place the electrical distribution system also on the sea bed in order to put electrical equipment near the load center, as suggested by common practice on all on-shore designs.

For subsea oil and gas development and processing fields, specialized equipment is required: main challenges to be faced are pressure containment, deep water depths, remote operation, maintenance, flow assurance, and oil recovery infrastructure. The reliability for the environment is a very important characteristic as well as the capability to make the exploitation of the subsea hydrocarbons economically feasible.

2.2.2 Power supply for offshore platforms

Depending on the requirements of the process and equipment on the installation, the power required by an offshore platform may be in the range of a few to hundreds of megawatts.

Power needed to operate an offshore platform can be provided from mainland electrical grid by a dedicated connection or from local gas turbines (GT) or diesel generator sets.

For example a platform consuming 100MW would have five or six gas turbines considering individual applications that need direct-GT-drives and redundancy constraints.

Offshore installations located at distances of tens of km from shore can be fed by AC cables connection: this is a simpler and lower cost transmission solution as besides cables and transformers, it does not need other major components such as power converters. For longer distance AC connection is not viable because of serious dynamic and reactive compensation issues so a valid alternative is offered by DC solutions.

There are also studies on the possibility to realize an offshore grid in order to enable energy transfers among different countries and offshore facilities like wind farms and oil and gas platforms [12]. In case such a grid will be developed, of course there will be no need of dedicated connections.

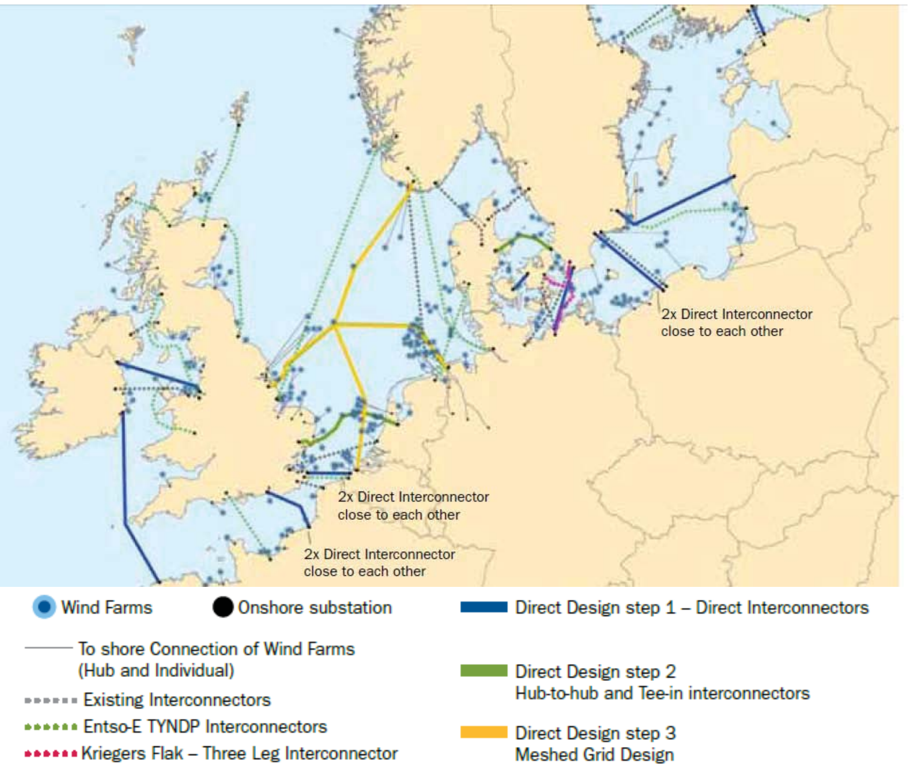


Figure 11- Example of an hypothetical offshore grid [12].

2.3 Renewable energy sector

Renewable energy systems generate electric power from the conversion, typically, through several cascade elements, of the kinetic and/or potential energy associated to primary resource. For example most tidal stream converters are similar to wind turbines since they harness the kinetic energy of flowing tidewater instead of air flows.

Apart from the particular technology they are based on (wind, wave, tidal) ocean energy projects have these common key components:

- Prime mover: it constitutes the interface between resource and power take off equipment, aimed at resource energy capture.
- Power take off (PTO): it is referred as the mean by which energy extracted from primary resource is converted into electrical energy.
- Control systems: they are used to optimize performances in the possible operating conditions.

- Foundations and moorings: they represents methods to secure energy converters to the seabed.
- Connection to grids: it is constituted by the electrical infrastructure to collect and transmit generated electrical power into the electrical grid.

Figure 12 depicts different PTO permutations representing the possible mechanisms for obtaining energy conversion from wave and tidal currents.

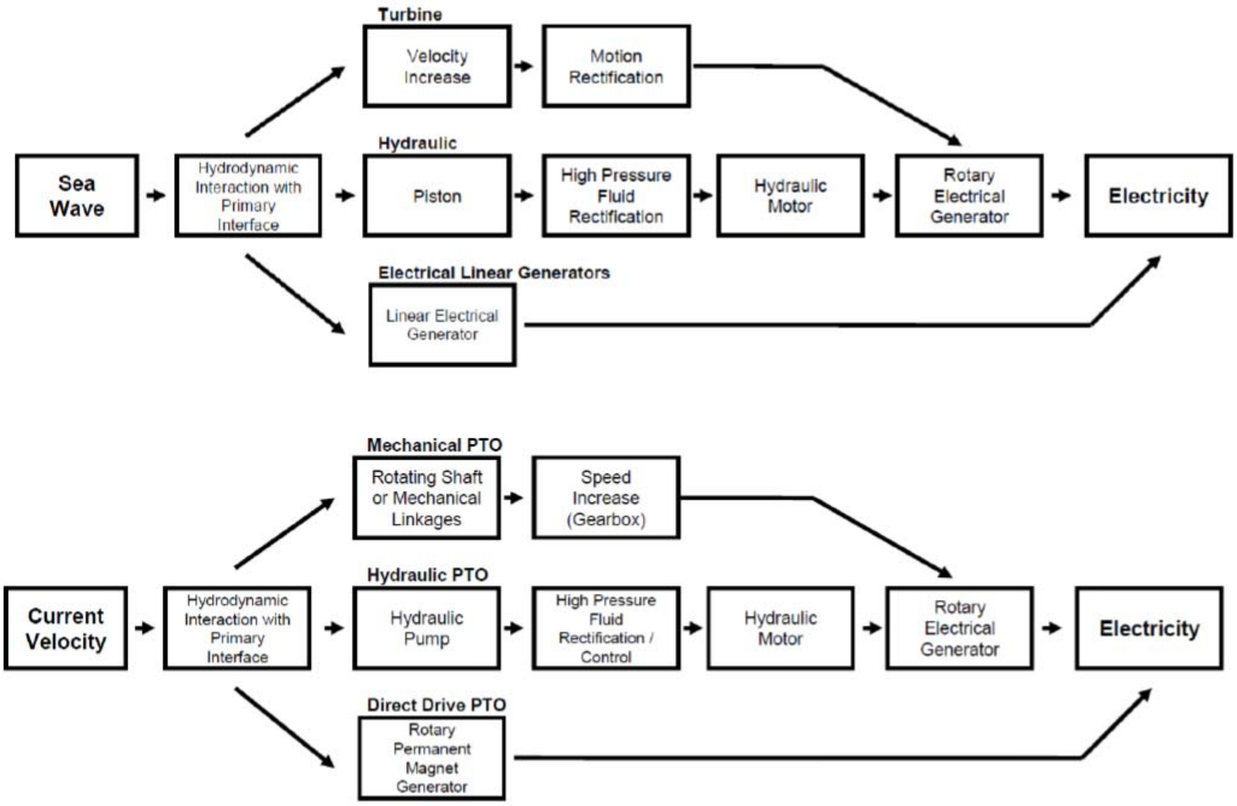


Figure 12- Possible PTO permutations in ocean Energy sector [13].

2.3.1 Offshore Wind farms

Offshore wind farms consists principally of these elements:
- wind turbine generators;
- offshore inter-turbine cables (electrical collection system);
- offshore substation (if present);
- transmission cables to shore;
- onshore substation (and onshore cables);
- connection to the grid.

The design of the electrical system is determined by specific site conditions, total power installed, characteristics of both wind turbine generators and the grid to be connected to. Wind turbine control and electrical systems are in constant evolution to provide improved characteristics and fault response to be compliant with grid integration issues.

For what concerns transmission and conversion technology there is a trend towards increased reliability in drive train design by using direct drive technology or implementing technical solutions aimed at improving reliability for geared designs. In the field of electrical generators permanent magnet ones (PMGs) are sensibly diffusing since they offer the possibility to reduce the nacelle mass and from the electrical point of the trend in generator technology is going from partial to full power conversion [2].

The turbine generator voltage, commonly 690 V, is stepped up to the inter-turbine voltage (typical values are 10, 20, 33 kV even if 45 and 66 kV are important emerging options): the transformer and switchgear are commonly put inside the turbine [1].

Wind farms close to shore with limited power can be directly connected to shore at medium voltage. However, as the distance from shore surpasses the threshold of more than a few kilometers, it is preferred to stepping up voltage level and use a limited number of high voltage cable, typically in the range of 120 to 150 kV.

Offshore substations largely followed offshore oil and gas practice, typically with a foundation structure (usually a jacket structure or monopoles) and a ‘topsides’ structure: the latter is built onshore, featured with all electrical equipment, and commissioned before the transportation to the site and installation on the foundation structure.

High Voltage Direct Current (HVDC) is increasingly being used: according to [1] this technology is likely to be used for the larger and more distant UK wind farms, and is considered to be cost effective for projects of around 500 MW with a cable route of around 100 km.

2.3.2 Wave and tidal farms

According to the possible ways by which energy can be extracted from waves different types of WECs (Wave Energy Converters) have been developed such as attenuators (like Pelamis, DexaWave), point absorbers (like Wavestar, CETO, SeaRaser), Oscillating Wave Surge Converter or OWSC (like Aquamarine Power), Oscillating Water Column or OWC (like Voith Hydro Wavegen), overtopping/terminator (like Wavedragon), pressure differential (AWS Ocean Energy), Bulge Wave (Checkmate Seaenergy), Rotating Mass (Wello Oy).

In a similar manner to wave energy devices different tidal energy converters (TEC) have been developed and can be classified in the following: Horizontal Axis turbine (like Siemens MCT), Vertical Axis turbine (like Neptune renewable Energy), Oscillating hydrofoil (like Pulse tidal), Enclosed Tips (like Open Hydro), Helical Screw (Flumill), Tidal kite (Minesto).

Typical conversion solutions used in wave and tidal power are presented in Figure 13.

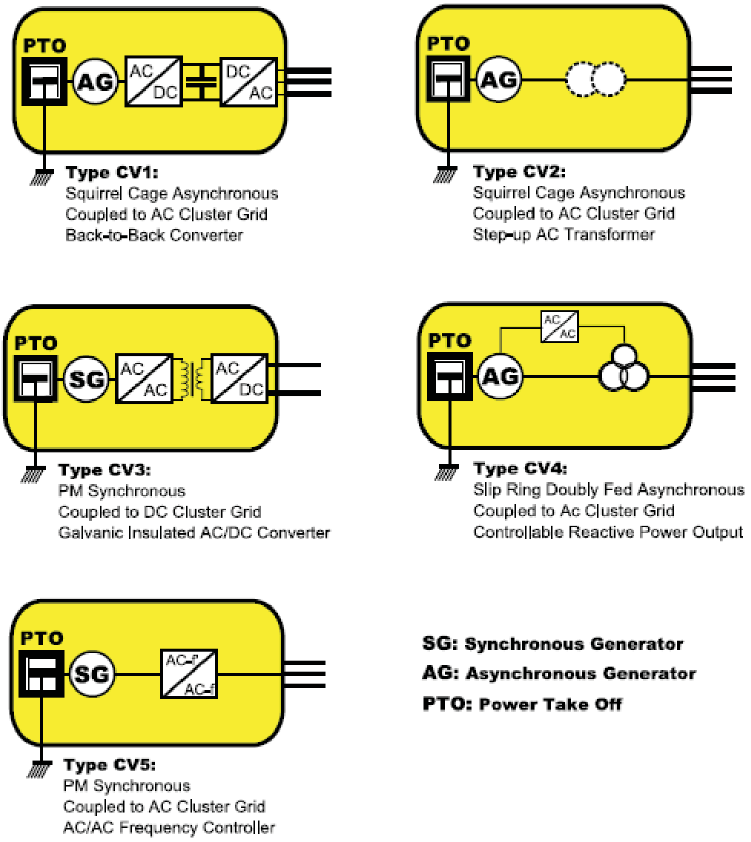


Figure 13- Generation units configurations used in marine offshore energy [6].

Marine generator technologies can be categorized in “fixed speed” and “variable speed”, the latter characterized by the presence of power electronics for interfacing with the grid, that can be individual for each device or shared also at cluster and farm level, this being a key difference in comparison with wind energy [6].

Fixed-speed generators are robust and economical but they must absorb significant torque pulsations being unable to store any associated significant energy. In addition reactive power can be controlled only using a fixed-speed synchronous generator or otherwise switched capacitors and static compensators. For variable speed category several options are possible:

- for variable speed individual units, having an embedded converter inside, optimum operational speed can be achieved.
- for cluster-coupled variable speed units a common converter is used in each cluster and the speed and electrical frequency vary proportionally with the average marine resource flow (tidal current speed, mean sea-state, etc.) in the cluster.
- for wave park-coupled variable speed, all generators have the same electrical frequency, which can either be constant or can be controlled more or less in proportion to the average marine power in the farm. Due to the fact that mechanical loading is higher than in the previous configurations, this option can be used when device-embedded energy storage systems (flywheels, hydraulic accumulators, super capacitors, etc.) are envisaged.

Due to the great variability of the primary resources, wave and tidal current conversion systems usually need the presence of power electronics and storage elements to provide a continuous, stable and grid-compliant, supply to the electricity network.

Both for WECs and TECs output power typically ranges from some tens of kW to some MW (1-2). To extract total resource potential at a given multiple devices are needed, therefore, not to create a dedicated connection for each converter, multiple device arrays, capable of collecting power outputs of several devices have to be realized.

At the moment the predominant focus of industry has been concentrated on developing, demonstrating and testing of single devices while important aspects to be investigated are array device interactions, hydrodynamic aspects, structural optimization of arrays, ecological impact of an ocean farm.

Maximum number of devices constituting an array is limited by acceptable voltage drop along the cable and its maximum capacity: several options for farm layout are possible, each of which can be associated to different levels of power losses, reliability and overall costs. It’s important to note that the actual layout of the ocean energy array is to be determined in accordance to geotechnical conditions and resource characteristics.

The layout options for arrays usually referred as “clusters” are shown in the following figure:

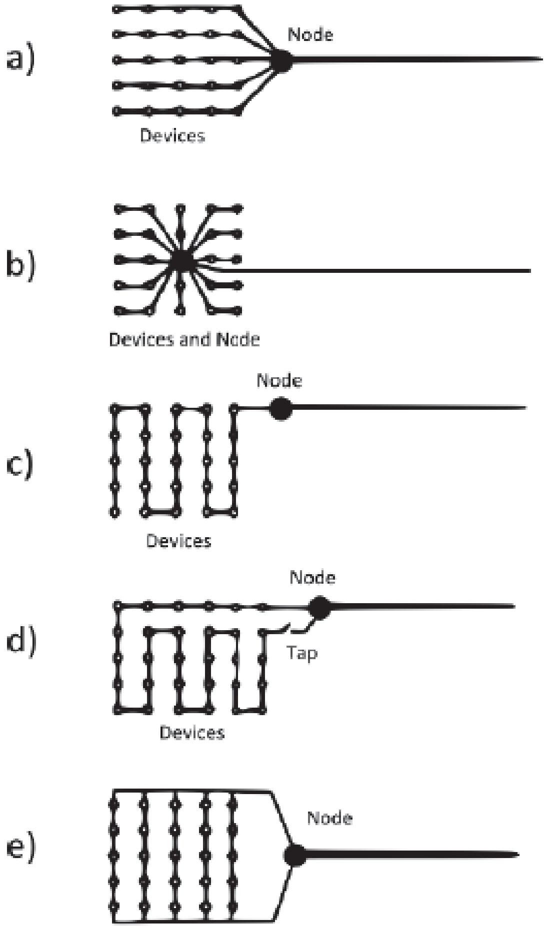


Figure 14 - Possible Ocean Energy Converter Array Layouts [14].

Where:

- option a) is referred as String Series Cluster and is suited for medium and large farms, both in AC and DC regimes

- option b), known as Star (Radial) Cluster is indicated for large unit farms both in AC and DC regimes
- option c), called also full string cluster is indicated for Small farms, both AC and DC regimes
- option d) is referred as Redundant String Cluster is suited for high risk farms in AC and DC regimes
- option e)consists of a series DC Cluster: it is indicated for small and medium farms in DC regime

Apart from clusters that generally refers to low/medium-voltage local collection system, a generic farm may have a step up transformation section and a transmission circuit/system. For integration into the grid several options are possible: apart from single device connection (individual transmission), suited for little farms, placed closed to shore for economic reasons, converters can be organized into one cluster connected to shore by one transmission link (single clustered farm transmission) or in several clusters, each of which connected with a dedicated link to the grid (clusters independent transmission), or each of which reaching a collection point, or substation, from which power can be evacuated by one transmission link (Multi-clustered farm single cable transmission) [15].

According to [6] typical voltage levels used in pilot projects are around 3 and 6 kV per device. Apart from the general considerations already made at the beginning of chapter 2 about AC and DC transmission alternatives, new possibilities of connections solutions, not used in the wind sector due to characteristics of WTGs, are possible for ocean energy farms: these possibilities are directly related to generation in DC capabilities: in fact if generation and collection grid is in DC, configurations depicted in Figure 15 can be adopted.

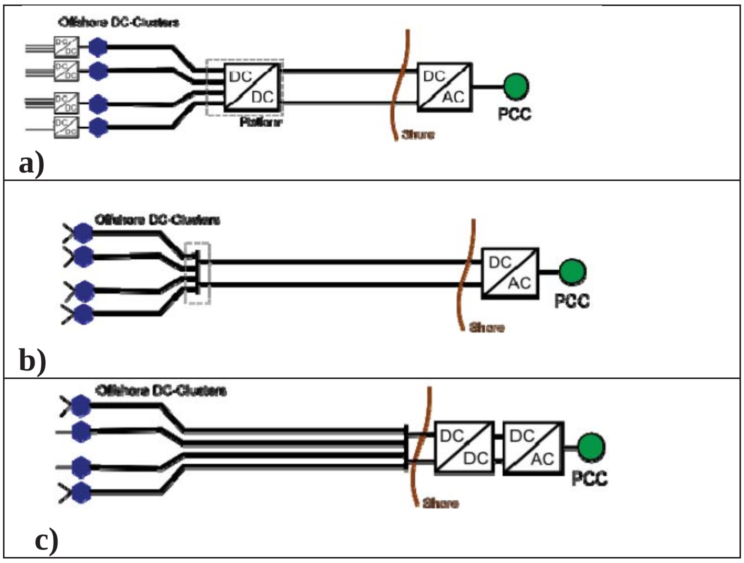


Figure 15 – DC collection related transmission configuration for ocean Energy farm [6].

In solution a) two offshore transformation steps are used for increasing the voltage from the generators to a suitable level of transmission. A increased voltage output can also be obtained by connecting the DC units in series (DC-Series Cluster) as shown in part b). For a small DC offshore farm, the topology shown in c) can be chosen , where compared to the HVAC transmission for AC farms, a DC transformer and a DC /AC converter are to be used onshore.

3 Power collection/distribution system

This chapter analyzes components constituting power collection systems typical of offshore renewable energy farms and components of subsea engineering relevant to oil and gas subsea systems.

Generally the distribution/collection system of an offshore energy farm would require the following elements [3]:

- cables to connect energy devices/converters (power cables, umbilical cables, fiber optic cables etc.)
- cable accessories as connectors, joints and structural accessories (hubs or subsea chambers)
- collectors and conversion equipment (hubs or subsea chambers, LV/MV or MV/MV substations, power converters, transformers etc.)

For small size farms some elements can be not necessary or some conversion equipment can be included in the energy converters.

Even if for wave and tidal applications conversion equipment and umbilical cables are currently device-specific and strongly depend on the generator type used, it is expected that, in the future, most of the marine energy technologies will be provided with on-board converters and transformers as it happens for wind turbine generators, characterized by standardized equipment directly installed inside the tower, while the deployment site will still define the design of the umbilical. Despite the fact that umbilical cables have been extensively used in the offshore oil and gas industry, ad hoc solutions for their application in marine energy sector might be required since they have to face with specific dynamic loads due to motion of the devices, particularly strong in wave energy floating technologies.

Subsea distribution system used in the oil and gas sector will be briefly described as representative of a part of subsea engineering that constitutes an important reference for the development of subsea devices useful for the exploitation of marine energy.

3.1 Cables

This paragraph describes the most important elements used to collect and evacuate power generated by energy converters in the offshore renewable energy sector and to connect subsea equipment to hosting facilities in the oil and gas industry.

3.1.1 Power cables

Electrical cables typically used for connecting wind turbine generators of offshore wind farms, and usually referred as "inter-array" cables, are medium voltage (MV) , three core cables (3C). Also medium voltage single core cable are available. Current carrying conductors of submarine power cables are made of copper or aluminum. Copper is more expensive than aluminum in relation to the current carrying capability, but allows a smaller cross section then requiring less material. There is no established best option because costs are very variable [16].

Investigations by research institutes are ongoing on carbon nano-tubes to make conductors with very high conductivity: from 1986 when high temperature superconductivity was discovered, some laboratory samples of cryogenic superconducting cables were developed, but at the moment avoided losses are not justifying technology changes, due to high energy demand associated to the cooling process [8].

Conductors are usually stranded from round wires and are generally designed according to standard IEC60228, Class 2: the use of hygro-expanding powder prevents longitudinal propagation of water.

A semi-conductive polymeric layer having the function of leveling the electric field outside the conductor forms the conductor screen.

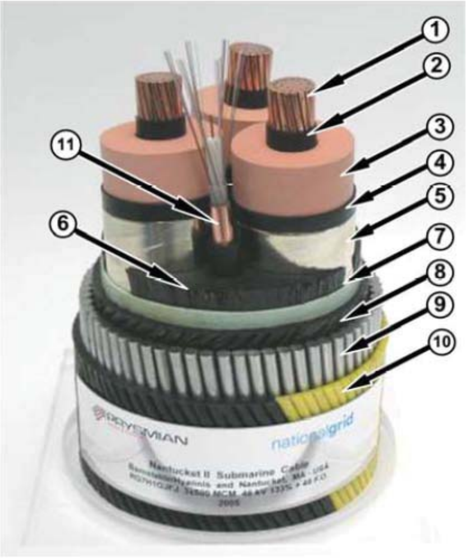
Cable insulation system offers an important barrier to potential differences between potential surfaces. Insulation material must be clear, even, mechanically robust, resistant to aging and temperature: currently best choices for insulating materials are ethylene propylene rubber (EPR) and cross-linked polyethylene (XLPE). In the past oil-filled paper insulated MV cables have been proposed and used. Compared to oil filled paper insulated submarine cables, XLPE and EPR insulated cables offer the following advantages:

- XLPE and EPR are solid dielectrics. They are maintenance free, no supervision and control of the oil level or oil leakage is necessary.
- XLPE and EPR insulated submarine power cables have lighter weight permitting longer continuous delivery lengths and easier handling during transportation and laying. The bending radius is small. The solid dielectric and the heavy steelwire armouring are superior to the paper insulated and lead sheathed cables and are much less sensitive to severe stresses to which submarine cables are subjected during transportation, laying and operation.

Figure 16 and Figure 17 show respectively the structure of a “wet design” and of a “dry design” subsea cable, respectively insulated by means of EPR and XLPE [16]. EPR has a better behavior with presence of water and so it is used for realizing wet design type cables: these cables don’t need lead or plastic sheath for water protection, while XLPE has lower dielectric losses and a higher capability of withstanding overvoltages.

The “dry design” cables are smaller, lighter and handier than “wet design” due to the substitution of lead sheath with a thin copper sheet, longitudinally glued or welded.

“Semi-wet” design cables are similar in construction to those of Dry design type, but lead sheath is replaced by a metallic shield made by copper tapes longitudinally or helicoidally applied.



1. Conductor
2. Conductor shield
3. Insulation – extruded EPR
4. Insulation shield
5. Metallic shield
6. Fillers
7. Binder tapes
8. Bedding
9. Armour
10. Serving
11. Fiber optic

Figure 16 - Wet design type MV subsea cable [16]

1. Conductor
2. Conductor screen
3. Insulation – XLPE
4. Insulation screen
5. Protection against water penetration
6. Lead sheath
7. Polyethylene sheath
8. Fillers
9. Binder tapes
10. Bedding
11. Armour
12. Serving
13. Optic Fiber

Figure 17 - "Dry Design" type subsea cable [16]

To give the cable a circular shape, fillers, generally made in polypropylene, are used. A binder tape is also present for gathering of insulated conductors inside a metallic shield.

The bedding is constituted by a layer of polypropylene that is in contact with the armor that, typically consisting of galvanized steel wires, gives the cable a proper mechanical protection against environmental, operation and installation solicitations.

Protection of the armor from abrasion during installation is offered by the serving, consisting of polypropilene strings.

Fiber Optic cables can be installed inside the cable to assure control and communication functions and are generally inserted inside a a polypropilene central structure.

In an array different sections of cable are normally used in order to optimize power exported: generally not more three different sections per array are used in order to minimize extra costs associated with logistic, operation and installation issues.

Typical nominal voltage for distribution cables is 33 kV, corresponding to a power transmission limit of a single cable of around 30-40MW: in fact cable larger than this would bring difficult to handle due to large diameters.

Studies to use conversion equipment at voltage level of up 72.5kV have been made [17] and some developers offers solutions and cables characterized by

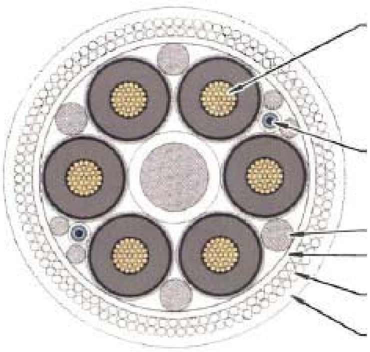
nominal voltage levels of 45kV and 66kV [18].

Several advantages can be obtained with higher voltages in the collection circuit: according to ABB [19], considering the same power installed the solution with an increased voltage level in internal grid is characterized by smaller circulating currents and then lower short circuit current, lower losses and voltage drops; these aspects allow the use of smaller conductor sections and enhance the power capacity of arrays which can then be less in number and composed by a bigger number of WTGs: this give also the opportunity of avoiding the construction of a MV/HV offshore substation.

According to a study of Carbon Trust [20] switching from 33kV to 66kV would lead to a small percentage of costs increase (12%) in front of a large increase in transmittable power (100%).

Normally used conductor sections are in the range of 150÷830 mm^2 and they corresponds to external diameters of 95÷145 mm and weight per length of 17÷45 kg/m [16]. For a more detailed overview of submarine cable systems it is possible to refer to [21].

It is worth to mention the technical solution implemented in Wave Hub test centre where connection to shore is obtained using a subsea MV, 6 core export cable power for the initial capacity of the site of 20MW: it consists of twin 300mm2 33kV triads and fiber optic cable, custom engineered by JDR.



Stranded conductors with longitudinal water blocking; semi-conductive extruded conductor screen; XLPE insulation; semi-conductive core screen;copper taper metallic screen

Fiber optic

Polypropylene fillers

Polyethylene inner sheath (armour wire bedding)

Armor package comprising double layer galvanized steel

Polyethylene outer sheath

Figure 18 – Subsea export cable of Wave Hub [JDR brochure on Wave Hub].

For offshore wind and oil and gas installations in deep water floating platforms have been proposed which cannot provide static termination points for submarine power cables: cable used in these applications are subjected to mechanical solicitations deriving from platform movement or sea currents (e.g heave, sway, torsion actions or a combination of them).

Similar issues arise for wave devices where part of the installation is subjected to rising and lowering movements or where the device has to re-orient itself to properly capture wave energy: some solutions can be taken as reference from oil and gas applications (e.g. risers) to be further and specifically developed for renewable energy field [22].

For these particular application “dynamic” cables are used as an alternative to the “static” cables previously described.

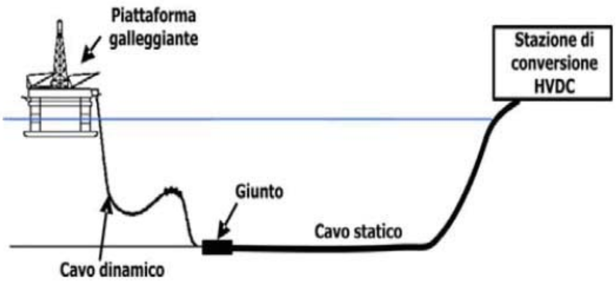
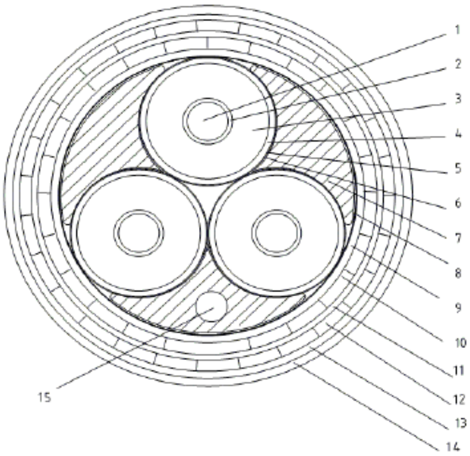


Figure 19 - Connection to the grid of a floating platform [16].

3.1.2 Dynamic power cables

As written above dynamic cables are designed to withstand mechanical stress associated to typical wave and current induced movement. They have a double armor with no lead sheath. Figure 20 represents the architecture of such type of cable.



1. Conductor
2. Conductor screen
3. Insulation –EPR or XLPE
4. Insulation screen
5. Metallic screen
6. Anti-corrosion polyethylene sheath
7. Binder tapes-fillers
8. Anti-corrosion polyethylene sheath
9. First bedding
10. First armor-galvanized steel
11. Second bedding
12. First armor-galvanized steel
13. External bedding
14. Polyethylene sheath
15. Optic Fiber

Figure 20- Structure of a dynamic cable [16].

To provide additional protection devices are offered in the form of bending stiffeners and bending restrictors described in the chapter of cable accessories.

3.1.3 Umbilicals and risers

Umbilicals or umbilical cables are cables that supply required consumables to an apparatus acting as a vital connection for its correct operation; they constitute a lifeline able to provide power, communications, electric and/or hydraulic control and production chemicals [23].

Subsea umbilicals are extensively used for subsea equipment and offshore oilfield development, acting an extremely important role in connecting surface installation and underwater equipment and represent an interesting element for the deployment of marine energy sector. Typically they have a flexible construction and consist of metallic and non-metallic materials, and load bearing armor wires or tubes.

Their mechanical behavior is of extremely importance in fact, due to typical operating conditions characterized by tension, torque and bending loads and the demanding environment in which they are installed and operated, their components are subjected to stresses and strains that require a specific design and high-tech construction [24].

Umbilicals connect the surface facility to the subsea equipment by means of an Umbilical Termination Structure or Assembly (UTS-UTA). From this structure, umbilical services are transported to the various subsea apparatus. Umbilicals can provide a single purpose or a multipurpose connection by a unique line: the latter solution is referred as integrated umbilical type.

For example an electro-hydraulic umbilical containing electric cables for power and signals transmission and high, medium or low pressure tubes for transporting hydraulic liquids and chemicals and fiber optic cables is the most common type used for general control purposes: relevant application concern the remote control, monitoring and chemicals injection of subsea wells from a hosting facility that can be located offshore (both fixed and floating or a ship) and onshore.

In the centre of the umbilical is put one element that can be for example a power cable, a tube, or a bundle of tubes, while the other elements are placed around the core, arranged on several layers: to assure a proper stable construction fillers are placed between the elements and an external layer of a plastic sheath can be applied [25].

A distinction between static and dynamic sections can be made for umbilical cables. Usually the segment that covers the water column between the host facility and the seabed is referred as dynamic if it is free hanging, while the static part is generally considered the segment laying on/under the seabed. Forces to which these two sections are subjected are different and this lead to the need of specific different design approaches, that for dynamic part are of increasing complexity with water depth progression.

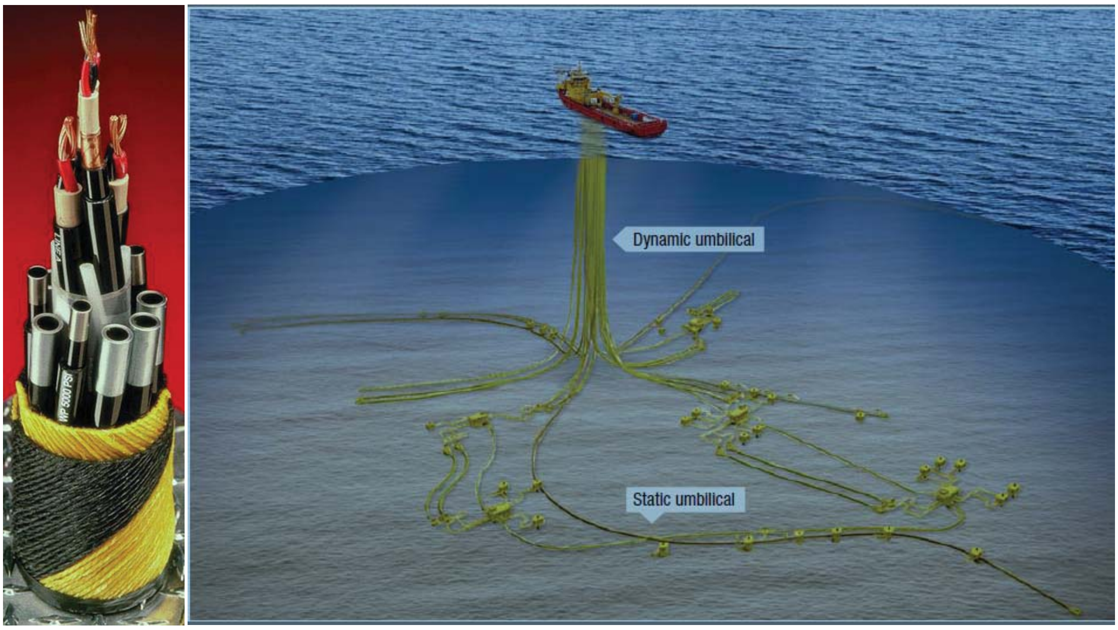


Figure 21 - An example of umbilical cable [25] and of static and dynamic umbilicals [26].

The configuration characterized by a dynamic section hanging freely between the topside facility and the seabed, is known as a free-hanging catenary: to provide support for the umbilical in the water column other configurations can be used too, like lazy wave, pliant wave, reverse pliant wave and steep wave. In the case of a fixed hosting facility, a part of the umbilical is usually installed and protected in a J-tube or I-tube (see chapter 3.2.3), as what happens to power cable in offshore wind farms and has static section characteristics. Dynamic and static sections can be combined by a transition joint or manufactured as one single unit. For dynamic umbilicals bending stiffener (see chapter 3.2.3) and buoyancy modules are used, that fitted around the umbilical provide the additional buoyancy needed by the configuration of installation, anchorage, which is a tether system that maintains the final part of the dynamic umbilical at the proper distance from the seabed in approaching the touchdown point and touchdown protection, subjected both to dynamic motions and abrasion from the seabed.

When talking about umbilicals, there are not standard products available on the market: they are all custom-designed to meet specific application needs. In the early years only thermoplastic hoses were used to carry liquids but moving towards deeper applications the use of different tube materials as, for example, super duplex steel tube, zinc-sheathed, seam-welded high-strength, low-alloy steel have been introduced. Steel tubes, having higher mechanical properties and enhanced corrosion resistance have been considered for carrying methanol, hydraulic and chemical injection fluids at deep and ultra-deep subsea installations, while seamless tubes are mandatory for deep and ultra-deep water applications for the high pressures involved.

Typical diameters range up to about 25 cm, with the inner tube with a size of up about 5 cm: the number and type of these tubes varies according to the complexity of functions demanded to the umbilical.

Other components development for oil and gas applications are risers. According to [27] a riser can be defined as a conduit to transfer materials from the seafloor to facilities located atop the water's surface, and vice versa: it is a particular type of pipeline developed for vertical transportation. Risers are usually insulated to withstand seafloor temperatures and can be either rigid or flexible.

Several types of risers exists like attached risers, pull tube risers, steel catenary risers, top-tensioned risers, riser towers and flexible riser configurations, as well as drilling risers.

Attached risers are used with fixed platforms, compliant towers and concrete gravity structures. They usually consists of several sections, the one closest to the seafloor is joined with a flowline or export pipeline, and clamped to the side the fixed facility. The next sections rise up the side of the facility, until the top riser section is joined with the processing equipment atop.

Pull tube risers are threaded up the centre of the facility that has preinstalled pull tube with a diameter wider than the riser. Then, a wire rope is attached to a pipeline or flowline on the seafloor, that pulled through the pull tube, brings the pipe along with it.

Steel catenary risers use the development of catenary equation that have helped to create bridges across the world: they can be used to connect two floating production platforms and on fixed structures, compliant towers and gravity structures. This type of “curved” riser can withstand limited motions.

Top Tensioned Risers are vertical riser systems that terminates directly below the floating facilities, that, even if moored, have laterally movement capability. Because risers are fixed to the seafloor too, vertical displacement occurs between the top of the riser and its connection point on the facility. The possible solutions for this issue can be constituted by a motion compensator with the function of keeping constant tension on the riser by expanding and contracting with the movements of the facility, or by buoyancy cans to be deployed around the outside of the riser to keep it afloat. In this way the top of the riser is connected to the facility by a flexible pipe, suited to accommodate the movements of the facility.

Riser towers were built to lift the risers from extremely water depths. This type of riser is constituted by a steel column tower that reaches almost to the surface of the water, is topped with a massive buoyancy tank, and contains the risers. Flexible risers are then connected to the vertical risers and ultimately to the facility above.

The Hybrid Riser System is a type particularly suited for application with floating platforms since its flexible risers can withstand both vertical and horizontal movements. Flexible risers can have different configurations as steep S and lazy S, that use anchored buoyancy modules, and the steep wave and lazy wave characterized by free buoyancy modules.

Buoyancy modules are structures of light weight material, usually foamed polymer, clamped to the exterior of an umbilical to reduce the submerged weight of the umbilical and to achieve the desired operational configuration.

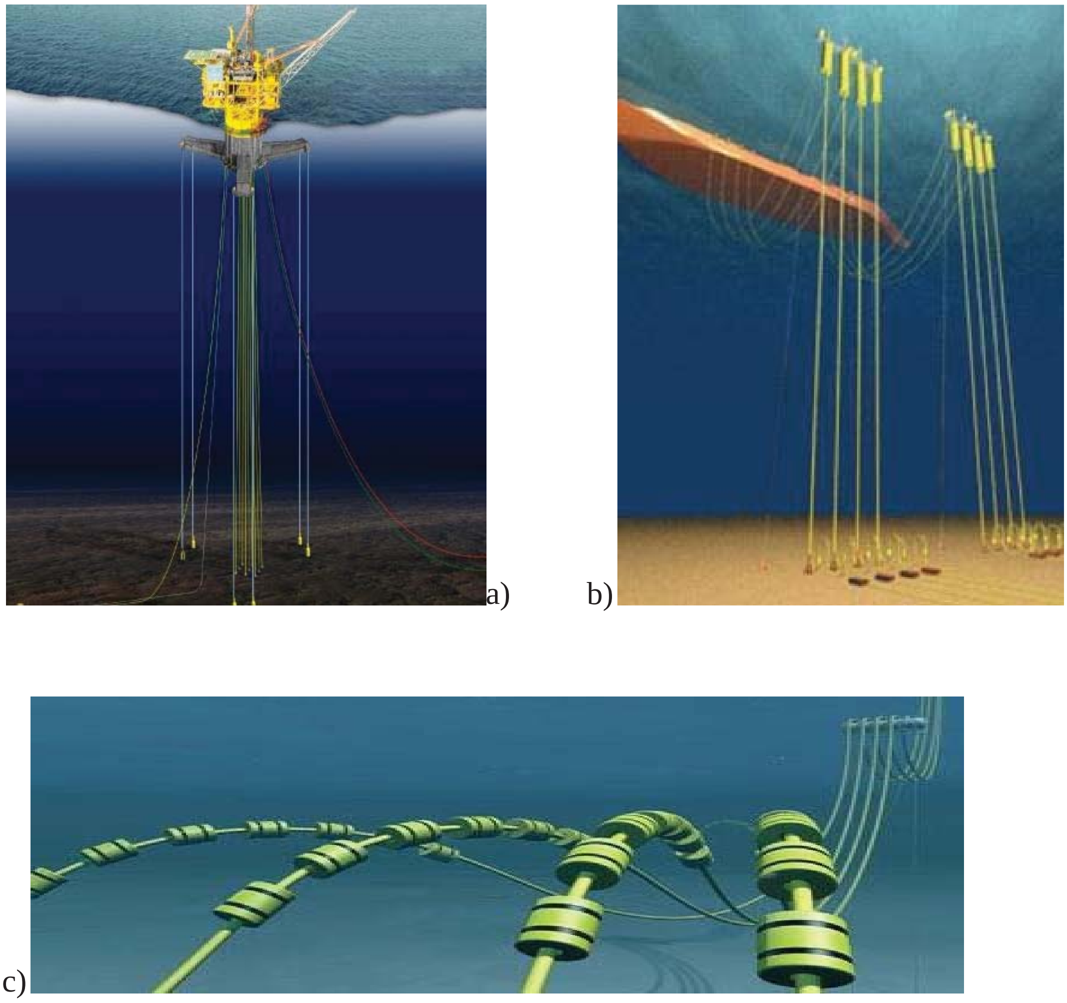


Figure 22- Top Tensioned Riser a), Hybrid Riser System b), and buyoncy modeules c) [27].

3.2 Cable accessories

3.2.1 Power cable joints

Joints or splices are used to connect two pieces of power cable, even of different conductor sizes and material, and represent a very important class of accessories requiring significant engineering, specialized equipment and team for their manufacture, deployment and installation. Thanks to improvement in engineering and installation methods joints don’t represent a weak point in cable connection systems anymore, as used to be in the past.

A quite big variety of cable joints exist: factory joints, installation joints, repair joints, flexible and stiff joints both for single core and three core cables, are available and are described in the following paragraph.

Factory joints connect semi-finished pieces of cable before the application of the armour: if during the manufacture of a cable a damage occurs in some parts factory joints can be used as well, after the removal of the damaged pieces.

This type of joints have a particular flexibility that allows the application of a continuous armouring over the joint in the factory using proper armouring machines. Their manufacture starts with the connection of conductors, using different welding methods, then the building-up of insulation: the insulation of the two cable ends is tapered to form a conical shape and then new insulation material is applied on them paying attention on avoiding the formation of voids, cracks other contaminations. Over the jointed insulation a lead sheath and a protective polymeric shrink tube are applied. In this way the factory joint represents an integral part of the cable core and can then pass to the following steps of the production line.

Offshore installation joints, known also as field joints, represent joints of the complete submarine power cable and thus comprise all of the elements/layers constituting the cable structure. The manufacture of this type of joints is made onboard a vessel or in the beach area.

Flexible installation joints are used when the offshore jointing of subsequent cable segments are required as for long cable routes. In this case the first length of cable is laid, then the vessel goes back to fetch the next cable length and once the end of the first cable is pulled up to the onboard jointing shack the still onboard second cable length is joined to the first cable with a flexible installation joint: the procedure of making such a joint is similar to that of factory joints. They have a simple design and can be easily installed.

Rigid joints or stiff joints have a rigid outer case, often a steel tube that has the double function of connecting the armors of the cable ends and of protecting the inner part of the cable joint. The steel tube allows the use of pre-moulded or prefabricated joint sleeves that have been the method of choice for polymeric land cables.

Rigid joints for their nature are transported and laid with more difficulty compared to flexible joints, but the advantages of prefabricated joint sleeves and the mechanical protection offered by the steel casing can prevent from using other components/elements.

Flexible joints are indicated to connect cables with small size differences while for large size differences rigid joints are preferred since they offer a higher mechanical protection.

3.2.2 Cable connectors

Connectors are devices that connect cables to devices, for instance a cable to an energy converter. Generally connectors can be of fixed design (bulkhead or stabplate mounted) or non fixed (free) design: in this case either plug or receptacle configuration is possible.

These elements are required to have two main qualities: efficient power transmission capability and easy and time saving operation and maintenance.

Apart from “non mateable” connections, or permanent/factory cable joints already described in the previous chapter, available connection devices for offshore applications are usually divided in “dry mate” and “wet mate” type: dry-mate connectors can be plugged and unplugged in an environment free of water, so while the ocean energy converter or the transformer/converter (or a generic other device of a substation/hub) is on the surface, or placed underwater inside an air chamber, while wet-mate connectors can be plugged with all elements already installed on the seabed thus directly in contact with water. The first are used for easily and or economically retrievable equipment: in the other cases the latter are preferred, even if they are more expensive than the dry type. Wet-mate connection systems are particularly useful for application in which a device have to be lifted to surface for maintenance without lifting all the cables to which it is connected, because for example cables have to be fixed to the seafloor to avoid displacement under high currents, as usually happens in tidal farms, or to avoid the necessity to hire a big vessel to host cables too. Wet-mate connectors can be of fundamental importance also for floating wind farms enabling the possibility to create a subsea distribution system instead of a floating substaion.

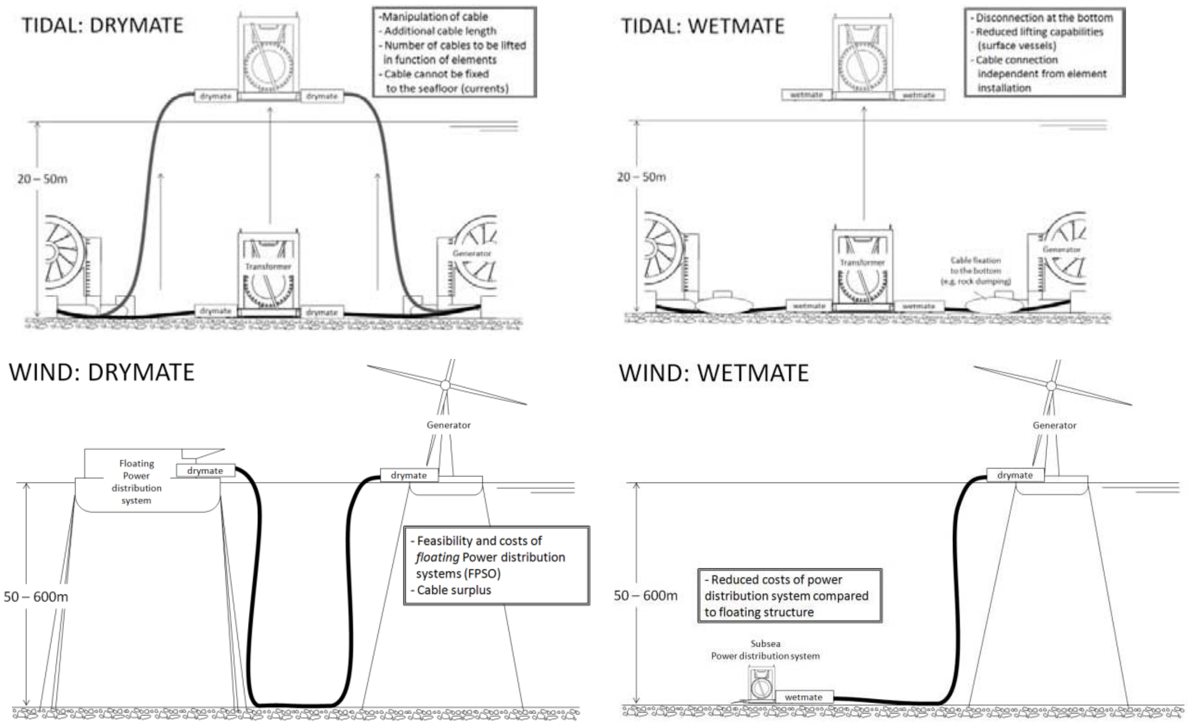
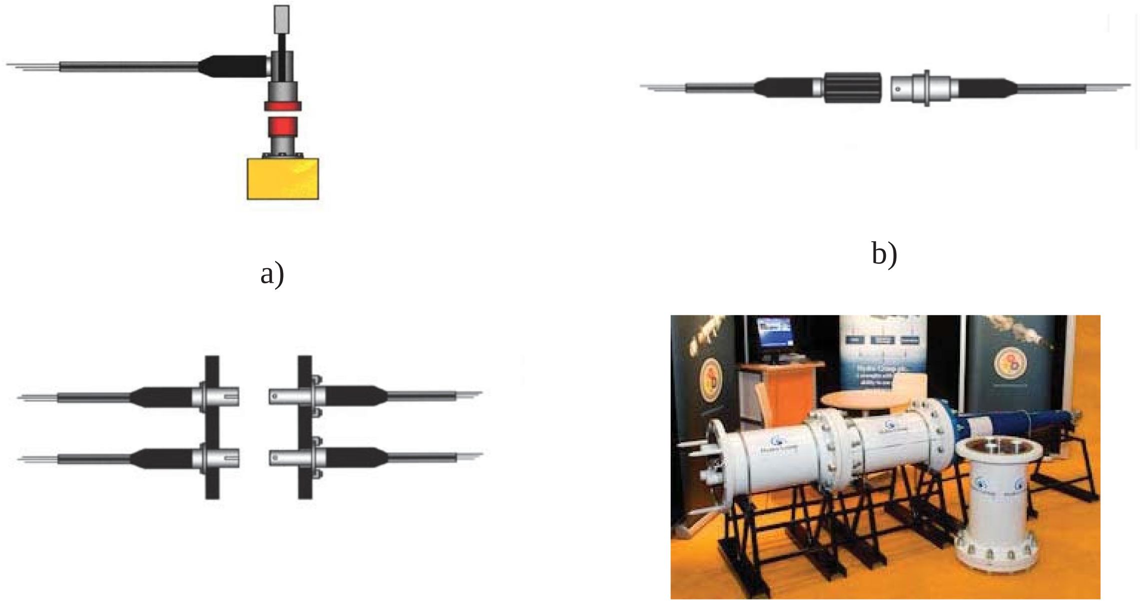


Figure 23 - Application of wet mate connectors [28].

Different types of wet mate connectors are available depending on their installation methods and are divided in Remote Operated Vehicle mate (ROV-mate), diver-mate, stab plate in accordance to the way of mating [3].

Connectors can be used for signal tand for power transmission.



a) b)

c) d)

Figura 24- Type of connectors: a) ROV-mate single connector (deep water), b) Diver-mate single connector (shallow water), Stab-plate multi-connector c) HRC Hydro Renewables Connector designed by Hydro Group [3].

Hydro Group Plc produced a dry-mate connector, specific for marine renewable technologies, capable of transmitting up to 6 MW power at 12 kV and has recently launched the 36kV upgrade, capable of both reducing installation time from 24 hours to less than 12 hours and of carrying triple power. Other examples of high voltage applications in the oil and gas sector are represented by 12kV Tyrihans and 36kV Ormen Lange fields. General Electric can offer a dry mate connector rated 145kV/700A that can be used from 26/45(52) kV rated voltage class equipment and is developing a high current wet mate connector rated 12kV/1800A for subsea compression, starting from the already available 12-24-36kV/500A examples.

Apart from connectors, other components are used to connect elements in a subsea/offshore environment, like couplers and penetrators: the first are ROV or diver operable, quick release connectors characterized by a wet mateable -poppet mechanism seals. The latter are considered more reliable than connectors, they are made up dry and are not serviceable subsea. They are usually used to terminate one end of a power cable in correspondence of equipment bushing and as a possible barrier between oil and water, gas and oil and gas and water.

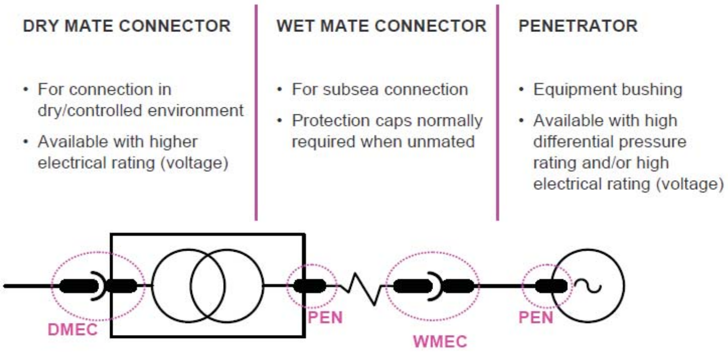


Figure 25 - Type of connectors and penetrators [29].

Recently the “POWERMATE” research project aimed at developing a wet-mate connection system that overcomes technical and financial issues related to common wet-mate systems: in fact these traditional systems mainly consists of sophisticated mechanical parts and sealing mechanisms to enable underwater electrical connection and thus, having a quite complex architecture, they require specific design and are characterized by a high failure rate [28]. The product of the research project should allow to carry out underwater connections including sealing, flushing and translation activities. The tool that is retrievable after each installation and can be used for several connections. The tool includes a water-tight chamber in which both connectors are hosted, then a dielectric liquid is used to flush the seawater out of the connection chamber: when no more water is inside the chamber the recovery of protection caps on connectors follows and the connectors can be connected together.

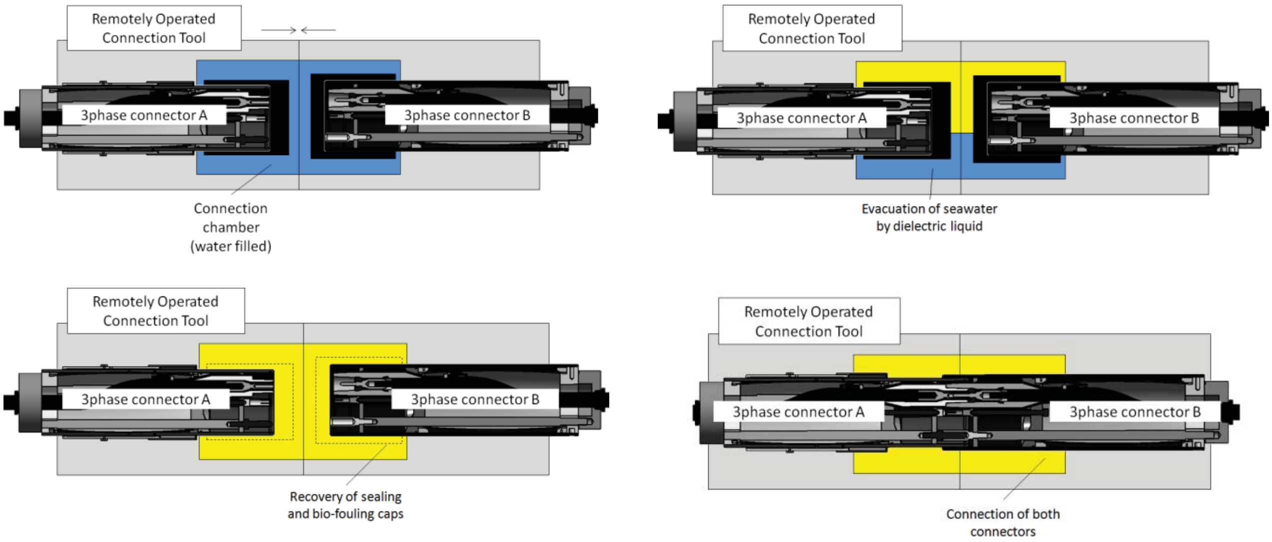


Figure 26 - Principles of POWERMATE connector [28].

POWERMATE aims to develop two types of wet-mate connectors, rated for 100 m water depth even if the particular; pressure-compensated design allows their use up to 3000m :

- High-Current Version: 3phase 1kV; 800A; 50Hz, 4 optical fibers & 12 data;
- High-Voltage Version: 3phase 24kV; 250A; 50Hz, 4 optical fibers & 12 data.

The tool can perform other functions such as cable pulling in, removal and recovery of protection caps (used to protect the connectors against bio-fouling), recovery of the free (unmated) connector after disconnection and monitoring of connection operations.

The method by which floating devices are connected to dynamic cables and interfaces between static and dynamic cables is very important for considering maintenance and installation issues of a marine energy farm: they both should avoid complicated and time costly operations. To answer the first aspect of this topic, according to [30], some developers have identified special methods like the proprietary connection arrangement studied for Pelamis, that allow the automatic connection of the cable to the wave converter, as well the one studied for OPT in which the cable can be connected without using a diver or ROV.

For floating WEC devices, different possible connection methods are described in Figure 27.

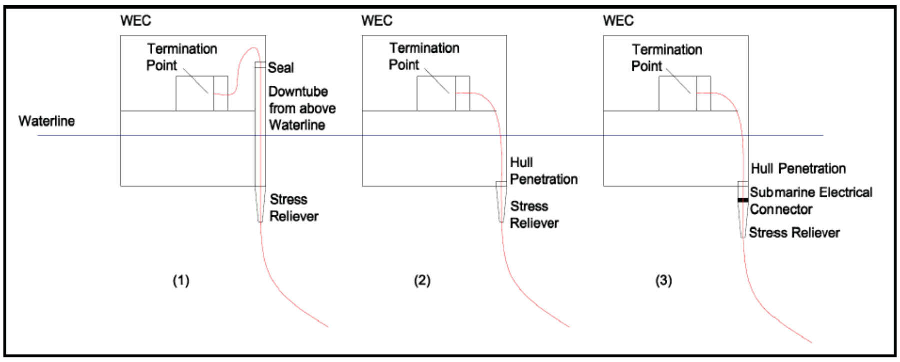


Figure 27 - Different connection scheme for dynamic cable, floating device (WEC) connection [30].

In option (1) the cable passes through a ‘downtube’, installed inside or outside the WEC, to cross the waterline: a stress reliever is needed to prevent from damages: in this system the cable can be drawn into the device on site and terminated within the WEC; in addition there is the need of caps to let the cable disconnected.

In option (2) the cable is routed directly out of water through a hull penetration, while the dynamic part of cable have to be connected onshore during construction and after moved to site for connection to the static section of cable already installed.

Option (3) is similar to (2) with the additional presence of a submarine connector, that allow one half of the connector to be fixed to the device, while the other is linked to the dynamic cable and is connectable on site, during installation by means of a diver, a ROV or a automatic system. This last two options are more expensive then the first since requires more components.

Figure Figura 28 shows different dynamic cable to static cable connection possibilities for a common floating WEC devices..

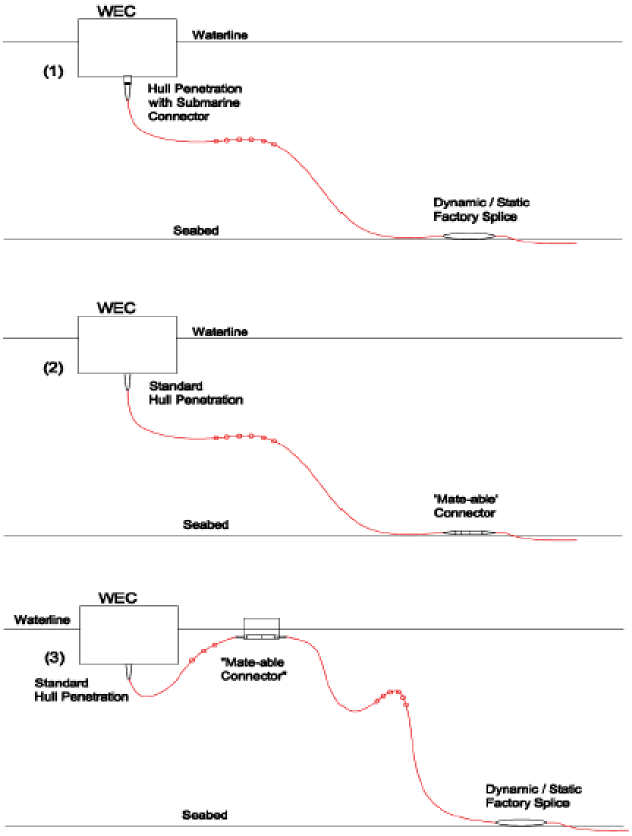
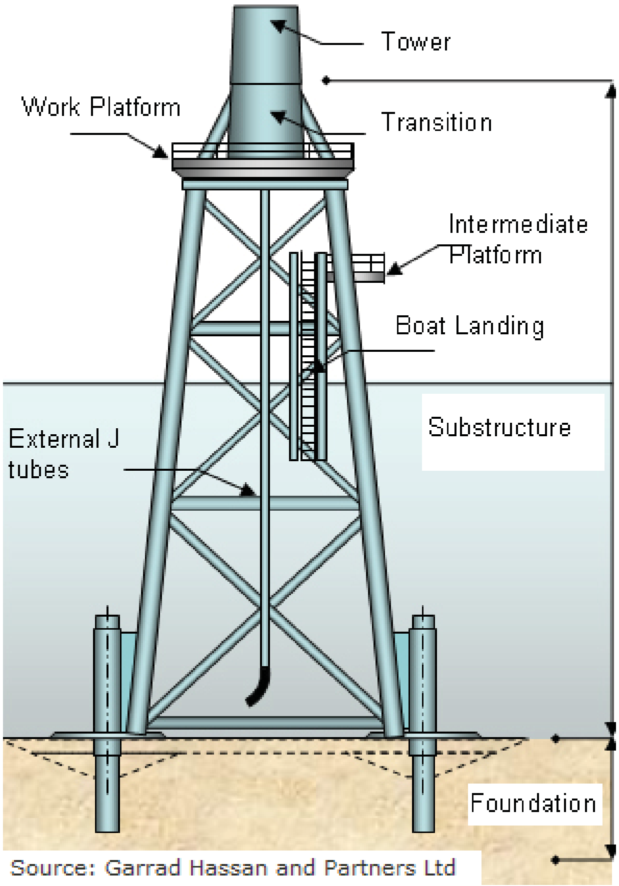


Figura 28- Dynamic to static cable interface options [30].

In option (1) the dynamic part of cable in a lazy-wave configuration is connected to the static cable by means of a factory (permanent) joint. In option (2) dynamic and static cables are connected through a mate-able connector, while option (3) is characterized by the presence of a floatation module that can be part of the WEC mooring system, that divide in two parts the dynamic section of the cable: at the sea bed the connection with static cable can be realized using a factory joint. The options presented are characterized by increasing costs.

3.2.3 Structural accessories and offshore cable termination.

A submarine power cable is generally buried in the seabed till wind turbine or platform base, then passes through a vertical tube from seabed to above water level, which is called J-tube or I-tube for its shape, by means of a pulling wire or pulling head: after a brief path in air it is constrained rigidly to the platform by an anchoring device called hang–off. J-tube/I-tube seals are used to prevent exchange of fluid within the tube with seawater.



Source: Garrad Hassan and Partners Ltd

Figure 29 - Example of J-tube [31].

Open air termination are possible only for moderate voltage levels. The cables are often terminated in encapsulated switchgear by Gas Insulated Switchgear (GIS) terminations, polymeric plug-in connectors, transformer termination; all these components require particular protective treatments, they must resist to corrosive actions and comply with applicable safety standard.

When a cable enters into a rigid joint enclosure or in a fixed structure like hang-off or cable or glands into floating facilities it encounters a discontinuity in bending stiffness. To prevent the cable from overbending and fatigue stress due to repeated bending, bending stiffener are used: they consist of elastomeric sleeves and have a conical shape that provide a gradual increase in bending strength. Other devices used for bending protections are the so called bending restrictors: they are modular and consist of a number of interlocked polymeric or metal shells around the cable that provide a specific bending angle for each interlocked element: they are used to block the bending radius, typically where there is the risk of overcoming minimum bending radius.

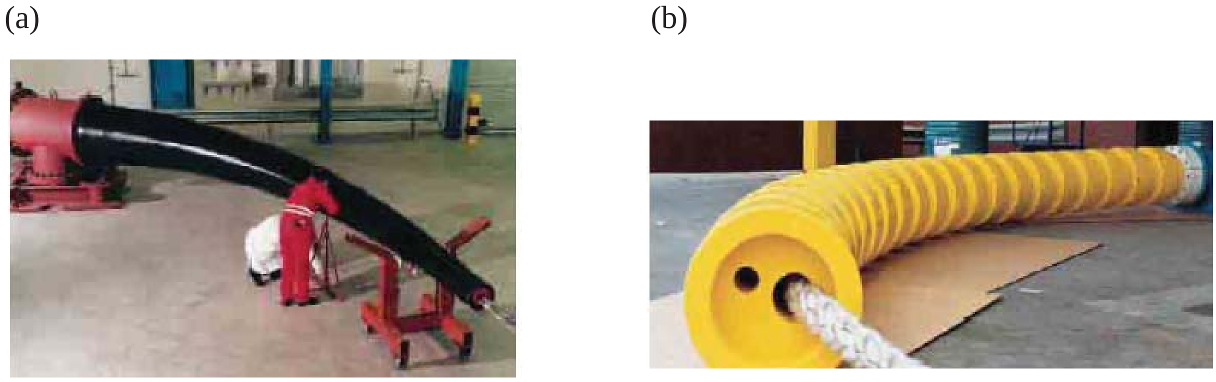


Figura 30 - Example of Bending stiffener (a),and bending restrictor (b) [16].

3.3 Collectors and conversion equipment

As already described in chapter 2 offshore wind turbine generators have a power conversion/switchgear unit inside their structure (nacelle, tower), while marine energy sector, having a huge variety of wave and tidal energy converters, shows a several possibilities conversion stages and farm layout to collect and export electric power to the main grid.

In order to give an overview of the state of art relevant to conversion equipment for marine energy applications, this paragraph describes collectors and conversion equipment currently in use in existing wave and tidal projects.

According to [32] under water or subsea connecting hub/substation/unit (sometimes referred as UCU) or substation pod (sometimes referred as USP) can vary from simple passive connection hub between two or more cables to a switching station with switchgear, transformers and other equipment and are used for offshore collection of power and signals/data. Since marine energy is in its very early stages design, testing, installation and maintenance methods of these devices have not been completely developed yet.

In the Wave Hub project, there is a subsea hub that acts as a junction box between the two triads of export cables, umbilical cables (tails or jumpers) to WECs and fiber optics [33]. Its design is made in order to allow no maintenance actions for the 25 year design life of the project, so all control function are performed above water without requiring the presence of additional components like switchgears inside the hub. The cable joints are all held within sealed, resin filled boxes. For cost saving purposes the hub structure is of gravity base type, further protected by rock dumping.

A little more complex substation unit have been developed by Ocean Power Technologies [34] with the aim of offering a universal platform for all marine energy generation technologies. It can collect up to ten offshore power generation devices into one common interconnection point and step up low voltages generated by offshore devices to medium voltage (11 kV–15 kV) can also provide full relay and fault protection, Supervisory Control and Data Acquisition (SCADA) capabilities, and remote control functions. The substation pod can also be configured for stepping-down voltage in order to provide shore-based power to other offshore electrical uses such as oil and gas, offshore carbon storage, marine aquaculture applications. A sample of 1,5MW has been built and tested for Santoña (Spain) project, and 5MW examples are expected to be built.

TECNALIA is working at the development of a subsea hub for power and data collection, KANPAI, which does not require using intermediate expensive umbilical connectors [35]. Connection and disconnection operations are carried out inside the hub, through terminals similar to the ones normally used on land, by using a “patent pending” inlet covering system that allows cost reduction achievements and rapid and frequent connection and disconnection actions. Electrical power protection and switching equipment and measuring devices or any other component can be put inside the hub.

The design for the BIMEP test site, expected for installation in 2014, comprise:

- five umbilicals cable inlets, one line output for grid connection;
- 13,2 kV rated voltage, and 1 MW maximum power individual input;
- interconnection and shore transmission of power, fibre optic data and auxiliary 220 Vcc power supply;
- Individual electrical protection, remote switchgear control and power and quality measurement for each individual umbilical cable;
- Easy and quick connection manoeuvre, eliminating the need for divers or ROVs.

According to [36] in the BIMEP test site, there are installed four 13.2 kV-5 MW junction boxes that collect the power generated by the WECs hosted by each berth.

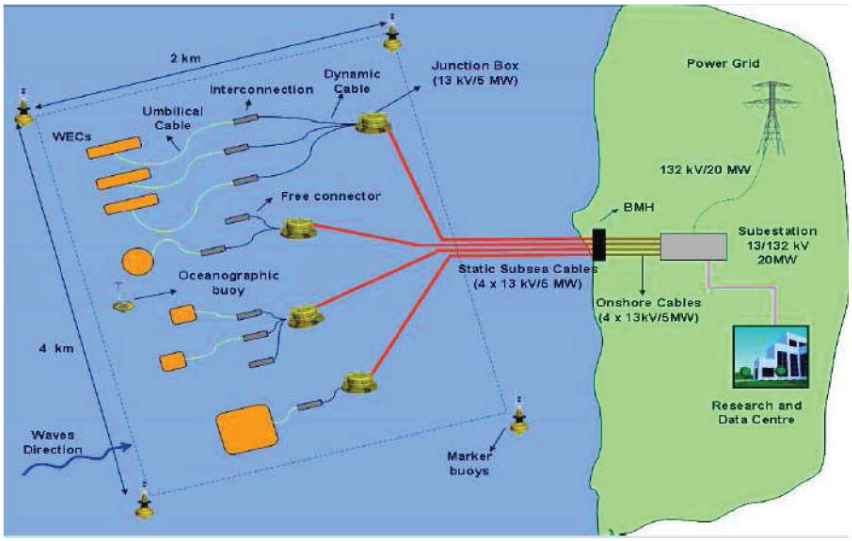


Figure 31 - BIMEP test site layout [36].

A subsea variable frequency substation, containing a DC busbar, common to three WECs, has been designed and partially tested at the Lysekil research site [37], according to the one-line diagram showed in Figure 32.

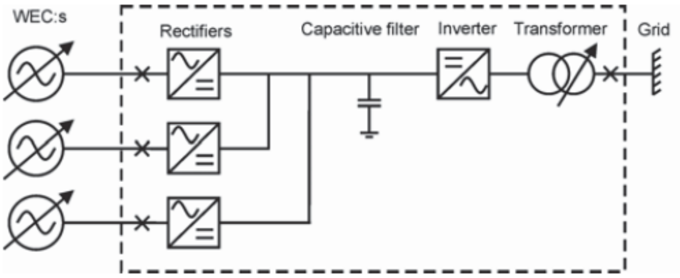


Figure 32 - One line diagram of the variable frequency subsea substation (inside dashed rectangle) [37].

Electricity is produced by each WEC with a wave shape characterized by varying electrical frequency and voltage amplitude. In the substation the voltage exiting by each WEC is rectified and the power is added to the power from other WECs.

Global output is then smoothened and converted to 50Hz AC, before transformation to a transmission voltage of 1 kV (line-to-line).

In the PLOCAN test site the electrical infrastructure will operate at 20 kV with the capability of delivering 15 MW and among other components, such cables and connectors, it will comprise:

- an underwater power transformer station connected to five entering dynamic cables of 0,5MW (50Hz) and 6,6 kV AC and to one exiting static cable of 5MW (50Hz) and 20kV

- a junction box holding the connection between the main hybrid cable coming from the land and the two secondary cables going to the marine devices. The junction box will contain a circuit breaker to protect the lines in case of electrical failure or allowing the disconnection of one part of the infrastructure for maintenance operations.

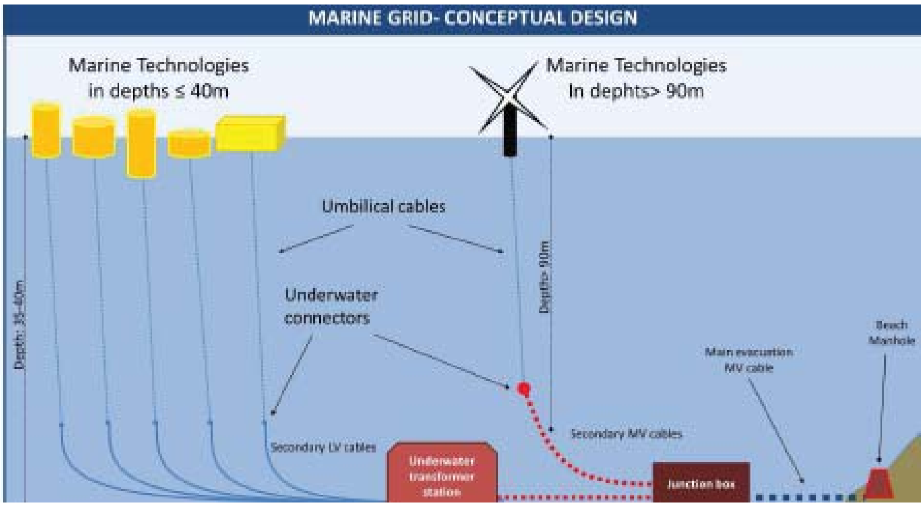


Figura 33 - PLOCAN Marine grid conceptual design [38].

In order to connect several energy converters belonging to a real marine farm rather than to a test site facility, switchgear features could be directly incorporated in WEC design as what commonly happens for wind turbine generator systems instead of using subsea junction boxes, or subsea hubs with switchgear equipment onboard [30]. Some of the possible solutions that can be developed to connect different energy converters are summarized in Figure 34.

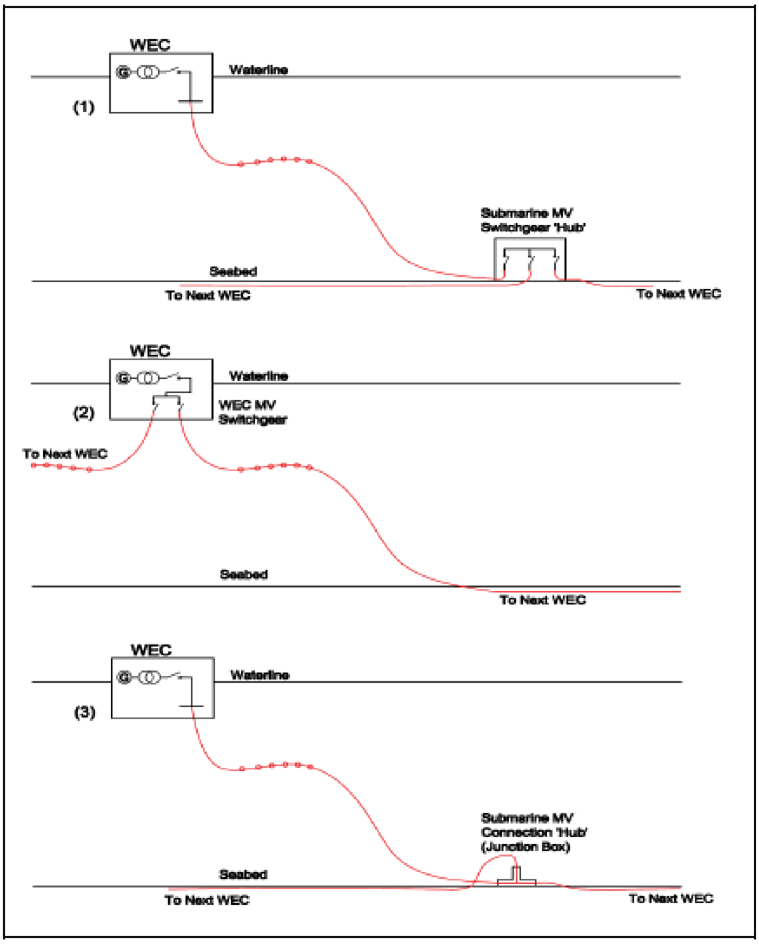


Figure 34 - Some possible switchgear configuration schemes are shown for a generic floating WEC device [30]

Option 1 shows a submarine switchgear unit which includes a protection circuit breaker for the WEC electrical system and dynamic cable; option (2) is the solution adopted in wind farms, with onboard switchgear, for in-out connection of wind turbine generator systems. In option (3) each dynamic cable connecting a WEC is connected to a ‘T’ connection hub placed on the seabed; in case of need for isolation of one dynamic cable section the entire circuit comprising all WECs must be switched out and isolated.

These solution can be utilized for radial connection of energy converters but other hub solutions can be considered for star cluster type grid configurations: these hubs generally, in addition to collection of generated power can condition it before transmission ashore; in order to perform these tasks they can contain a combination of power electronic converters, LV and MV switchgears, energy storage systems.

Subsea switchgear systems have been developed by several manufactures like Siemens, ABB, GE Vetco Gray, MacArtney and OPT specially for oil and gas applications, as described in the following paragraph.

3.4 Subsea distribution systems

This paragraph offers an overview of subsea distribution systems used in the Oil and Gas. Distribution systems provide support for executing underwater operations, they are therefore related to the operation control strategy, typically “hydraulic” having slow response time and low flexibility, requiring large umbilical and suited for shallow waters, “electro-hydraulic”, more rapid in response, with increased complexity and flexibility and enabling to move to deep waters and finally “all electric”, suited for ultra deep applications [40].

A subsea distribution system is called to perform several functions like hydraulic and/or electric power distribution, communication and chemicals injection distribution in order to assure control functions from topside facility to subsea equipment. The principal components are [41]:

- subsea umbilical termination assembly (SUTA)
- subsea distribution assembly or unit
- hydraulic and/or electrical flying leads (HFL/EFL)
- subsea accumulator module
- topside umbilical termination assembly (TUTA)

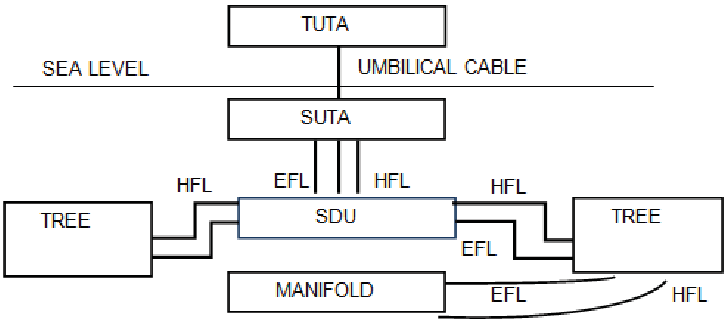


Figure 35 - Subsea distribution Block diagram [41].

The SUTA, placed subsea, provides the distribution between the umbilical and subsea equipment and is designed to:

- terminate the umbilical
- distribute the hydraulic, chemical and electrical supplies to the flying leads (see later)

The SUTA is mounted onto a special base that is installed onto a subsea foundation such as a mudmat. It is typically equipped with multiple quick connect plates (MQC), a mounting steel structure, a lifting device, electrical connectors, field assembled cable termination.

The subsea distribution assembly (or unit), a unit similar to SUTA, is designed for in-field distribution of hydraulic and electrical supplies and communication signals. It consists of an hydraulic and an electric distribution module (HDM and EDM): the first consists of MQC plates and has the function of distributing hydraulic fluids and chemicals to the subsea trees, manifolds and other devices, while the latter consists of electrical connectors, cables and sometimes of an electrical step down transformer.

The flying leads or jumpers are special links for distribution of hydraulic, electrical, optical signals and supplies, that provide the necessary connections to subsea equipment. Jumpers are usually terminated with either a wet mateable connector, coupler or penetrator.

Subsea accumulator modules store hydraulic fluid to assure that adequate pressure is always available for subsea system.

Topside umbilical termination unit provides hydraulic, electrical and fiber optic termination.

In order to access new unconventional petroleum reservoirs, the trends of subsea oil and gas applications is to further move offshore, into deeper waters and clustering more subsea areas with larger size than in the past, moving directly on the seabed activities historically made on platforms or offshore facilities (subsea processing): as a consequence more electric power is required as well as higher currents and voltages, accompanied by a strong demand for further development in subsea electrical components and systems. Typical power and frequency range requested elements of subsea system are summarized in Table 1.

Table 1-Power ad frequency ranges of subsea systems elements [42].

Element	**Power**	**Frequency**
Control	3-10kW	50/60 Hz
Pumps	1,5-2,5 MW	0-85 Hz
Compressors	6- 13 MW	0-250Hz
Total distribution systems	20-150 MW	50/60 Hz

To move pumps and compressors located on the seabed it is required to provide variable speed drives, due to uncertainty in reservoir data, that can be located topside or directly subsea as depicted in Figure 36.

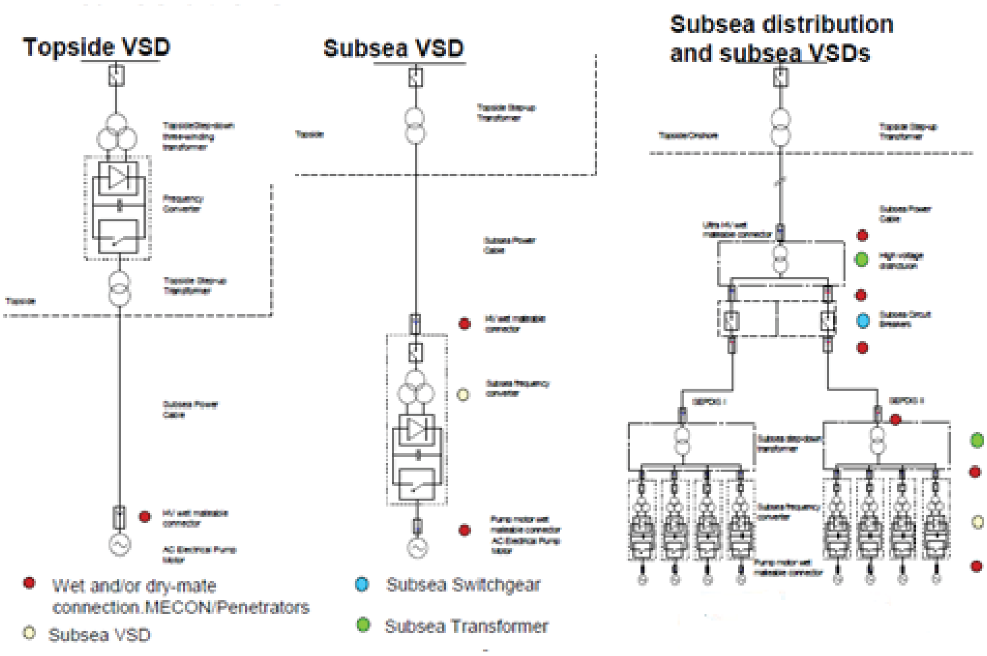
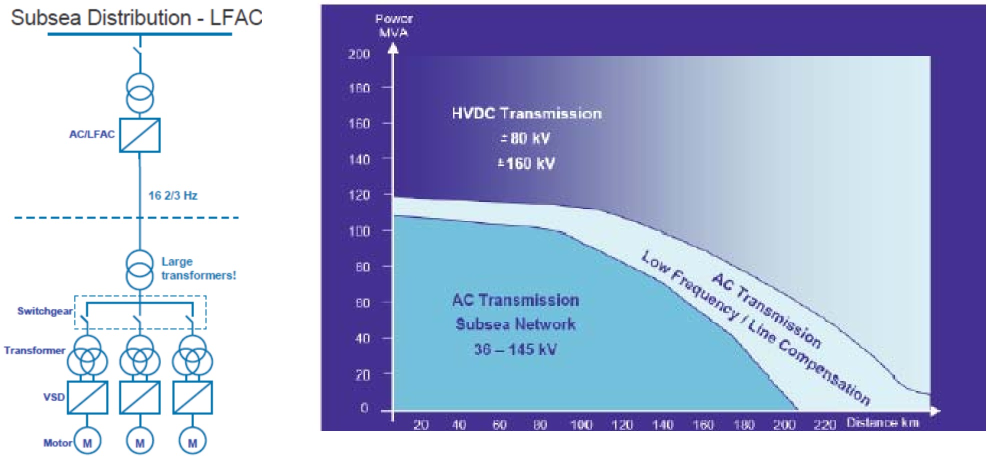


Figure 36 - Solution for power supply to subsea equipment [42].

If several subsea electrically fed devices are present there is the need of HV distribution system with HV components.

Example of such systems are Troll Pilot project, Ormen Lange Subsea Gas Compression project: for these projects several components have been designed like cable termination and penetrators systems qualified according to IEC (12kV/300A, 12-24/600A and 36 kV/700A), subsea switchgear modules, subsea transformers (and frequency converters (ranging from 3 to 15 MVA) [43].

A different option is represented by subsea DC distribution systems (by using HVDC technology) and low frequency subsea systems (LFAC) [30].



a) b)

Figure 37 - LFAC distribution systems a) and field of application for different transmission technologies b) [30].

According to [30] studies suggest that LFAC is feasible for power-distance couples from shore of about 50 MW/600 km.

A typical subsea power supply string with relevant components is represented below.

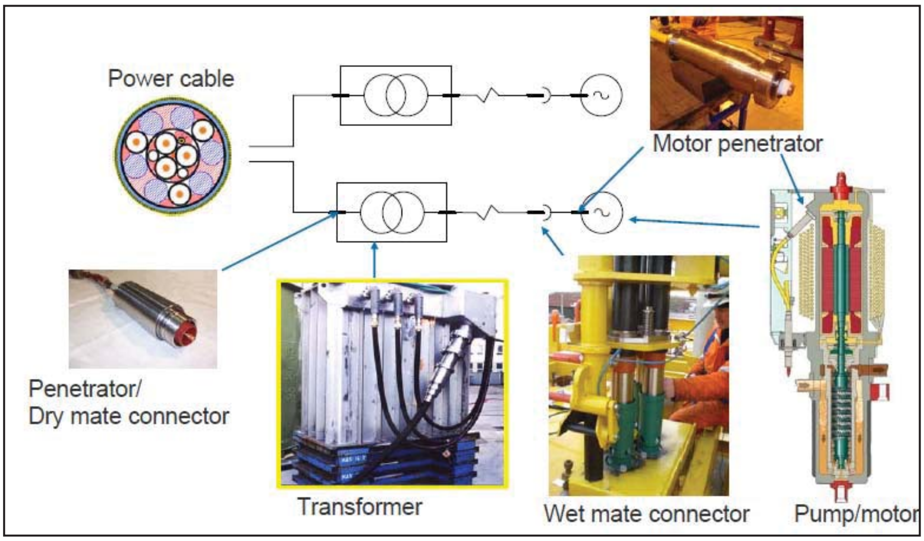


Figure 38 - A typical subsea power supply string [30].

Subsea transformers are available in a wide range of voltage and power levels. Typical examples are:

- 20MVA 120/22kV main step down transformer,
- 15MVA 22/3.7/3.7kV transformer for VSD compressor.
- 750kVA 22/2.85kV transformer for VSD pump,
- 15MVA 38.25kV/6.2kV, 200Hz,
- 5MVA 22/6.6, 67Hz.

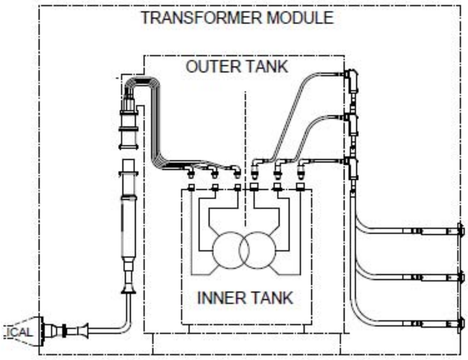


Figure 39- Example of a possible subsea transformer layout [30].

Examples of available rating for subsea switchgear modules are:

- 24kV/500A,
- 24kV/1800A,
- 36kV/800A,
- 36KV/3000A.

Deep and ultra deep applications in which the over mentioned electrical equipment is called to operate are extremely harsh: the system has to face with very high pressure and corrosive environment, providing at the same time all the electrical functions normally requested on shore or even more. Additionally, since the accessibility is difficult and limited, the electrical system need to be reliable, compact and capable of requiring less regular maintenance actions as possible. Installation and retrieval have to be possible without the need of large vessels and/ or heavy tools. Modular solutions seem to be the most adequate to respond to all these issues.

4 Power transmission

This section of the report is aimed at providing an overview of the electrical transmission systems for offshore energy applications. The focus will be on the main HV components: static cables, Alternating Current (AC) and Direct Current (DC) transmission system, substations. Here will be outlined the current state of the most relevant technologies.

4.1 HVAC/HVDC

As anticipated in the previous chapters in order to limit the losses and/or number of separate cables necessary to connect offshore energy farm with power rated higher than 30 MW or distance from shore > 20 km, the connection with onshore HV grid is useful to be made with High Voltage HV system, operated AC or DC.

This choice between AC and DC system is mainly depending on the distance to be covered from the onshore and offshore substation.

4.2 HV export cables

The cables employed for the grid connection of offshore energy farms are both Underground Cables and Subsea Cables types. The underground cables connect the substation to shore and the subsea cables are from shore to energy farm. The main difference between the two types is the armoring, present in the subsea cables to consent the significant tension due to cables weight and dynamic forces (vessel movements) presents during the installation. The armoring also has the function of mechanical protection during installation and for unexpected loads as fishing gears, anchors.

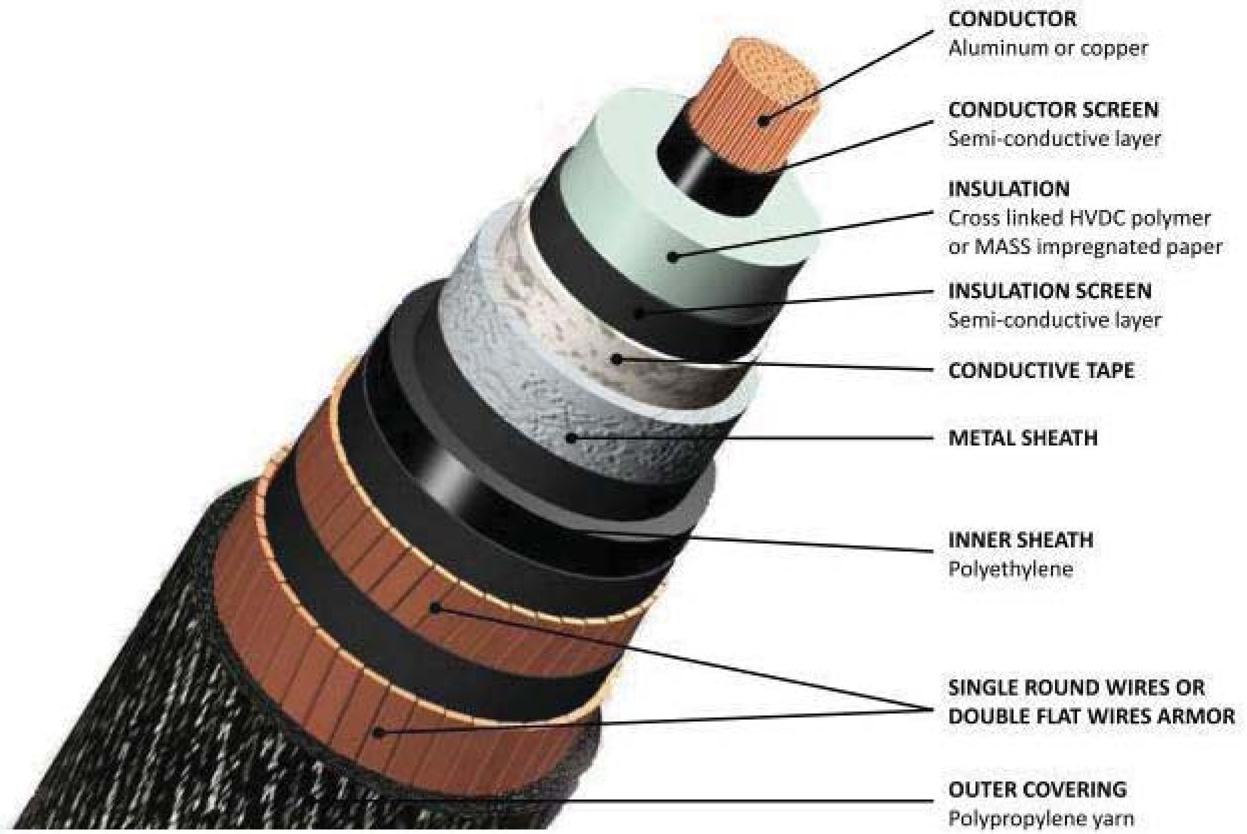
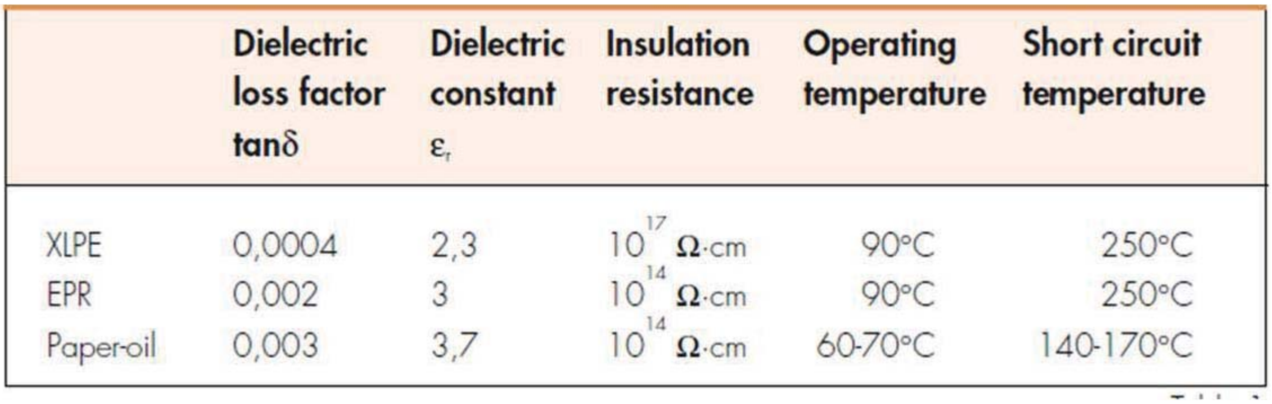


Figura 40 - Single core submarine cable, AC or DC [source: Europacable].

The above figure shows the composition of the layers for a typical one-core submarine cable. The conductors is made by copper or aluminum, with stranded or Milliken [8] wires. The insulation may be made both with extruded polymers or mass impregnated paper. Cross linked polyethylene XLPE is mainly used for AC application while mass impregnated MI is more compliant for DC cases.



	Dielectric loss factor tanδ	Dielectric constant ε_r	Insulation resistance	Operating temperature	Short circuit temperature
XLPE	0,0004	2,3	10^{17} Ω·cm	90°C	250°C
EPR	0,002	3	10^{14} Ω·cm	90°C	250°C
Paper-oil	0,003	3,7	10^{14} Ω·cm	60-70°C	140-170°C

Figura 41 - Cable insulation properties [source: Nexans]

The above table shows the characteristics of the different insulations. The insulation layer is contained between two cylindrical semiconductor screens that compensate the irregularities present on the surface of the conductors and on external shield. Due to radial symmetry, with this method the electric field in the insulation layer is uniform and is avoided any particular stress of the dielectric capacity.

Metal sheath and polyethylene inner sheath forms a mechanical protection and avoid the moisture ingress in dielectric insulation. Single or double layer of armor wires are the tensile structure that permit the cables are laying on large deep of water. Generally, these armoring layers are made of galvanized steel wires and will be copper made for single core HVAC cables, due to high parasitic losses in ferromagnetic steel wires.

4.2.1 AC Underground Cables

High Voltage AC Cables 60 – 150 kV

High voltage cross-linked polyethylene (XLPE) power cables in the voltage range of 60 to 150 kV are state of the art technology for Europe's distribution underground networks [58].

The technology has been in commercial use for more than 25 years. Since then, high voltage cables have proven to be a reliable power distribution component. When integrated into distribution networks, high voltage underground cables can be applied in lengths up to 100 kilometers. For AC new projects, XLPE cables are the preferred solution.

Extra High Voltage AC Cables above 220 kV

Cross linked polyethylene cables (EHV XLPE Cables) are the core technology to underground Extra High Voltage (EHV) power transmission lines (AC 220 kV – 400 kV). EHV XLPE cables are recognized as a technology that performs well based on the requirements established by the International Standard IEC 62067.

4.2.2 DC Underground Cables

High Voltage Direct Current (HVDC) underground cables have been in commercial use since the 1950's [58]. Today, two HVDC cable technologies are available:

Single core mass impregnated cables MI

Figura 42 – Mass impregnated DC cable [source: Prysmian]

This type of cable is currently the most used. It has been in service for more than 40 years, has proven highly reliability and can be provided by European manufacturers at voltages up to +/- 500 kV and 1600 A DC which corresponds to a maximum pole rating of 800 MW (presently in service) and bipole rating of 1600 MW. Conductor sizes are typically up to 2500 mm2 (at transmission capacity of 2000 MW bipole).

Polymeric cables, e.g. XLPE

Polymeric cables are only used in Voltage Source Converters VSC applications that allow the power flow to reverse without reversing the polarity.

Figura 43 - Extruded XLPE DC underground cable (background) [source: ABB].

To date this technology has only been applied at voltages up to +/- 200 kV (in service with a power capacity of 400 MW). There are projects at an advanced construction stage at the voltage of +/- 320 kV and 800 MW power and ongoing projects at 1000 MW per bipole, but it is expected to increase the voltage and power in the near future.

Self-contained fluid filled (SCFF)

Self-contained fluid filled (SCFF) cables have also been used for very high voltage and short connections due to the hydraulic limitations.

Figura 44 - SCFF HVAC cable [source: Prysmian]

4.2.3 AC Subsea Cables

HVAC subsea cable are XLPE insulated, normally are three core, but also single core is produced. The 3 core cables can contain an optic fibers connection [62].

Three-core submarine cables usually have steel wire armor. Single-core cables have non-magnetic armor.

Figura 45 - Extruded XLPE HVAC submarine cable [source: ABB]

Single-core cables can be laid separated or close. Close laying gives lower losses. Separation eliminates mutual heating but means higher losses in the armor. The induced current in the armor can be high, up to the same value as in the conductor. Single core XLPE submarine cables have nominal voltage up to 400kV/1000MVA while 3 core is limited at 275 kV.

4.2.4 DC Subsea Cables

High Voltage Direct Current (HVDC) subsea cables have been in commercial use since the 1950’s. Today, two HVDC cable main technologies are available. They are mass impregnated MI and XLPE extruded:

Mass-impregnated HVDC subsea cables

Mass-impregnated subsea HVDC cables do not need oil feeding from the ends and have as such no limitation in length. Mass-impregnated cables are composed by a very high viscosity impregnating compound which does not cause any leakage in case of cable damage or failure. Compared to oil filled cables, the compact design is also an advantage for deep water applications.

For the deeper water middle section, a double flat wire armour layer was used. The figure below shows the cross section of the deep water cable.

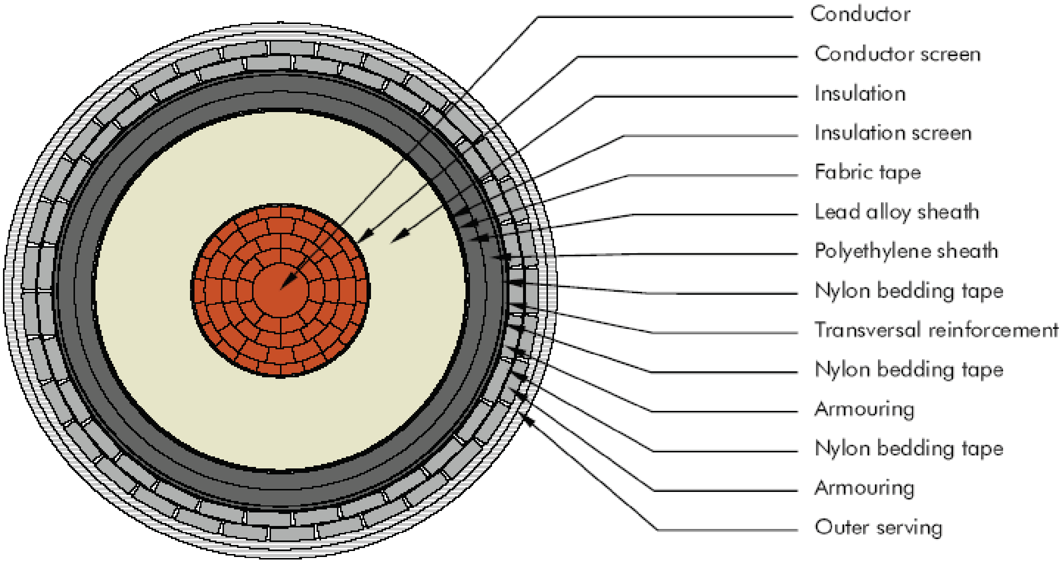


Figura 46 - Mass Impregnated subsea cable [source: Europacable]

Mass impregnated cables currently have nominal voltage up to 600 kV, 2000 MW with bipole configuration. Main suppliers of HVDC MI cables are ABB (Sweden) and Prysmian (Italy).

Polimeric Extruded Insulation Cables

Extruded insulation cables consist of an inner semi-conducting screen layer, the XLPE insulation compound and an outer semi-conducting insulation screen, extruded simultaneously. Extruded cables can use only with VSC HVDC transmission systems having the ability to reverse power flow without changing the voltage polarity.

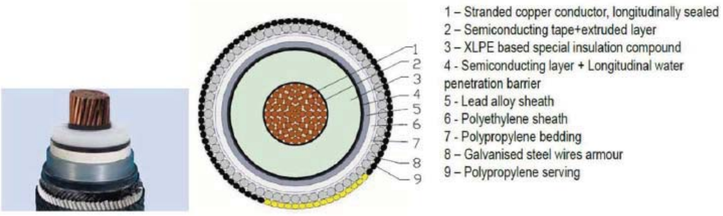


Figura 47 - Polimeric extruded subsea cable [source: ABB/Europacable]

A semi-conducting water swelling tape is then applied between the outer semiconducting screen and the metallic sheath in order to limit water propagation along the cable core in case of cable damage. The metallic sheath is made of lead alloy, over which a layer of polyethylene compound is extruded. XLPE requires an impervious metallic sheath to be applied over each core to avoid direct contact with water.

Instead XLPE an EPR compounds can be formulated in such a way as to give an excellent performance in terms of both electrical reliability and ageing, thus removing the need for an impervious metallic sheath (the so called "Wet Design").

The “armouring” includes bedding, armour and serving, applied in one common process. Armour is made of one layer of galvanised steel wires.

Serving is made of polypropylene strings that provide a high degree of abrasion protection and reduce cable friction during laying.

Three cables (two power and one optical cables) were laid and buried simultaneously in a bundle configuration

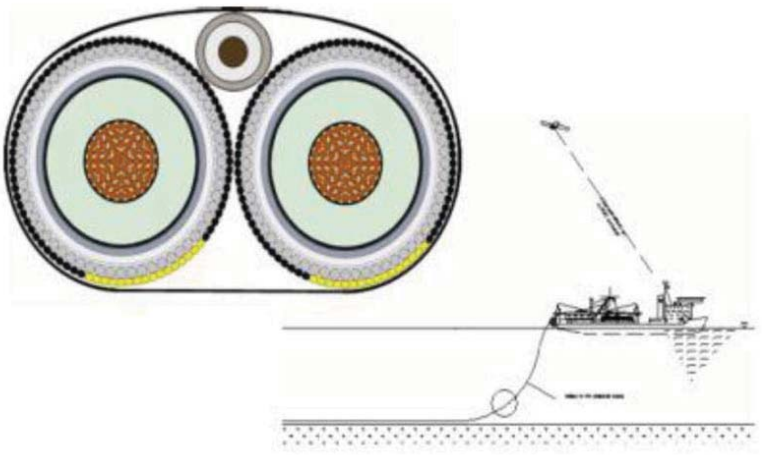


Figura 48 - Polimeric extruded 2 cores subsea cable [source: Europacable]

This methodology provided several advantages:

- reduced installation time
- reduced costs for protection
- it avoids leaving the cable unprotected on the seabed.

HVDC polymeric insulated cables, employed with VSC DC systems have nominal voltage up to 300kV and power capacity up to 1000 MW.

Main suppliers of HVDC polymeric extruded cables are: ABB (Sweden), Nexans (Norway), Prysmian (Italy).

<u>Low pressure oil filled cables as HVDC subsea cables</u>

Paper insulated oil filled cables are highly suitable for HVDC transmission for distances up to approximately 50 km due to hydraulic circuit limitations. The insulation system in these cables is constantly under oil pressure to avoid the formation of cavities when the cables are cooled down and the oil contracts. Oil filled cable systems have been qualified for use in AC and DC operations. Usually this type of cable isn’t the best suitable solution for offshore energy applications.

Lapped Thin Film Insulation PPL

PPL is a new frontier of insulation systems, composed by a lapped non impregnated thin PP film. Actually over final development, can operate up to 90°C and support high electrical stress, making it suitable for deep and very long subsea cable.

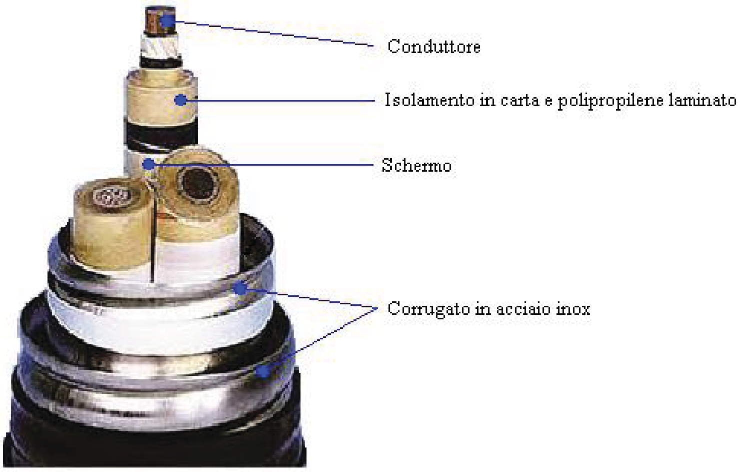


Figura 49 - Lapped thin film insulated subsea cable.

The HVDC cable system was subject to a test program as recommended by CIGRE TB 219.

4.3 HVAC High Voltage Alternating Current

An High Voltage Alternating Current HVAC offshore power connection system consist of:

- Offshore platform hosting transformers, switchgears, FACTS and ancillary,
- protection and control devices
- Subsea HVAC cable, usually 3 core cable + optical fiber
- Shoreline located subsea/underground cables connection facility
- Underground HVAC cable
- Substation connecting to the main grid with transformers, switchgears, FACTS
- and ancillary, protection and control device

A typical layout of HVAC connection for a wind farm is in the following figure [63]:

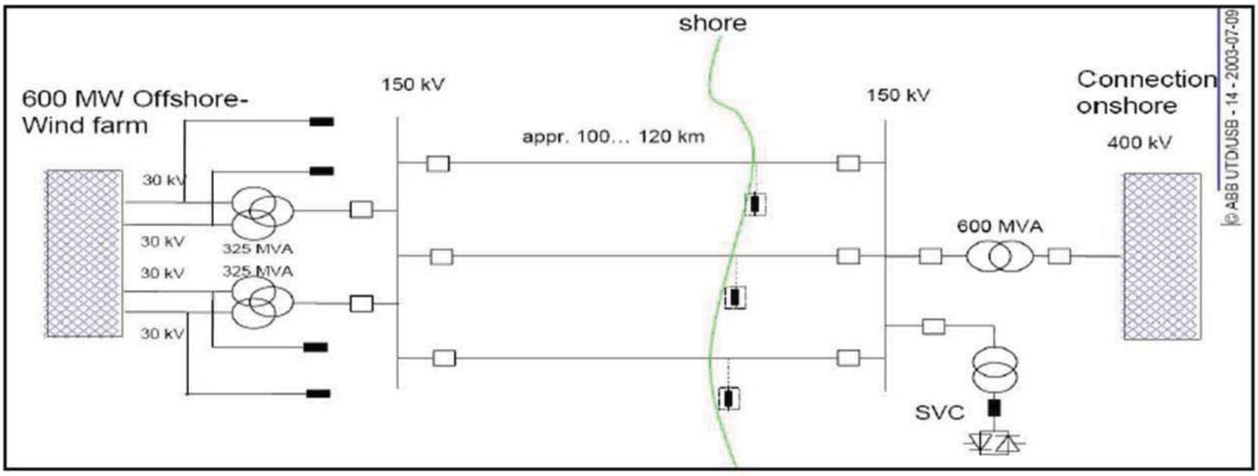


Figura 50 - HVAC connection scheme of large offshore wind farm [source: Orecca]

The type of cables to be applied in offshore AC transmission depends on the power to be transferred and the distance. If no intermediate compensation is possible or feasible, 150kV AC is used up to 120km.

The power transportation capacity of an AC offshore cable is limited by the maximum allowed temperature, which determines the maximum current and secondly by the distance, which determines the reactive power required by the cable. HVAC transmission involves a capacitive current, since the insulation materials act as a capacitor.

For long AC cables, a large part of their current-carrying capacity is used for the capacitive charging current (i.e. reactive current), so less active power can be transferred to the grid onshore. The charging current increases linearly with the voltage and also linearly with the length of the cable. Since the maximum current is constant and the total current equals the square root of the sum of the active and reactive power, a nonlinear relation results between the power that can be transferred by an offshore cable and its length. Beyond a certain distance, depending on the voltage level, the capacitive charging current exceeds the current rating of the cable itself and no power can be transported.

The large amount of capacitive reactive power need to be compensated in order to limits the current (and loss) and control the voltage of the power system.

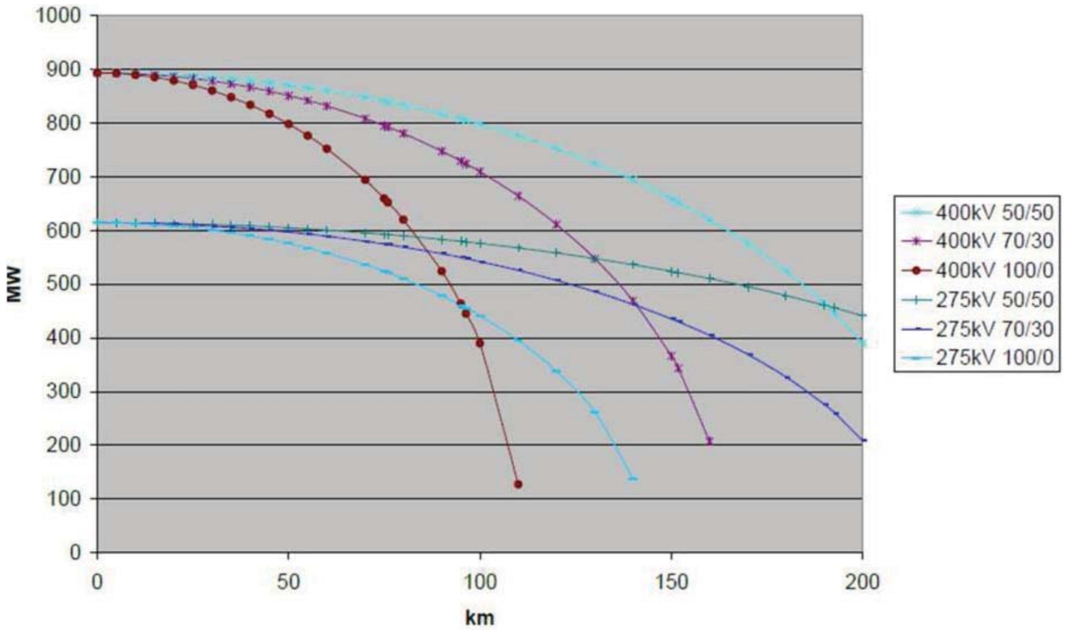


Figura 51- Influence of reactive power compensation on real power capacity of HVAC cable transmission line [source: Entso-e].

The previous figure shows the impact on a subsea line (formed by 3 single core 1000 mm2 cables) of the reactive power compensation split between offshore and onshore (100/0, 70/30, 50/50). As is above highlighted the employ of reactive power compensators has a great influence on the power transmission system capacity [55].
The Flexible AC Transmission Systems FACTS are the electrical system dedicated to these goals.

4.3.1 FACTS Flexible AC Transmission Systems

IEEE define a flexible alternating current transmission system (FACTS) as "a power electronic based system and other static equipment that provide control of one or more AC transmission system parameters to enhance controllability and increase power transfer capability." The main purpose of these systems is to supply the network as quickly as possible with inductive or capacitive reactive power that is adapted to its particular requirements, while also improving transmission quality and the efficiency of the power transmission system.
FACTS systems perform the following tasks:

- Control voltage under various load conditions
- Balance reactive power (voltage, transmission losses)
- Increase the stability of power transmission over long distances
- Increase active power stability

Main suppliers include ABB [64], Alstom Grid [65] and Siemens [66].
The FACTS system may be classified as follow, inside at two main groups related to the insertion mode in the power transmission system, Shunt and Series Compensation.

<u>A - Shunt Compensation:</u>
SVC – Static Var Compensator
STATCOM – Static Synchronous Compensator (fast VSC)

<u>B - Series Compensation</u>:

FSC – Fixed Series Compensation

- Increase in Transmission Capacity

TPSC – Thyristor Protected Series Compensation

- Increase in Transmission Capacity

TCSC – Thyristor Controlled Series Compensation

- Damping of Power Oscillations
- Load-Flow Control
- Mitigation of Subsynchronous Resonance SSR

A - Shunt Compensation

Shunt compensators may be inserts in any node of the power connection systems to balance the reactive power and increase maximum transmittable power, regulate the voltage profile, and prevent voltage instability. Parallel reactors prevent overvoltages under low load conditions.

SVC Static Var Compensator

The key component of a parallel reactive power compensation system is the Static Var Compensator SVC.

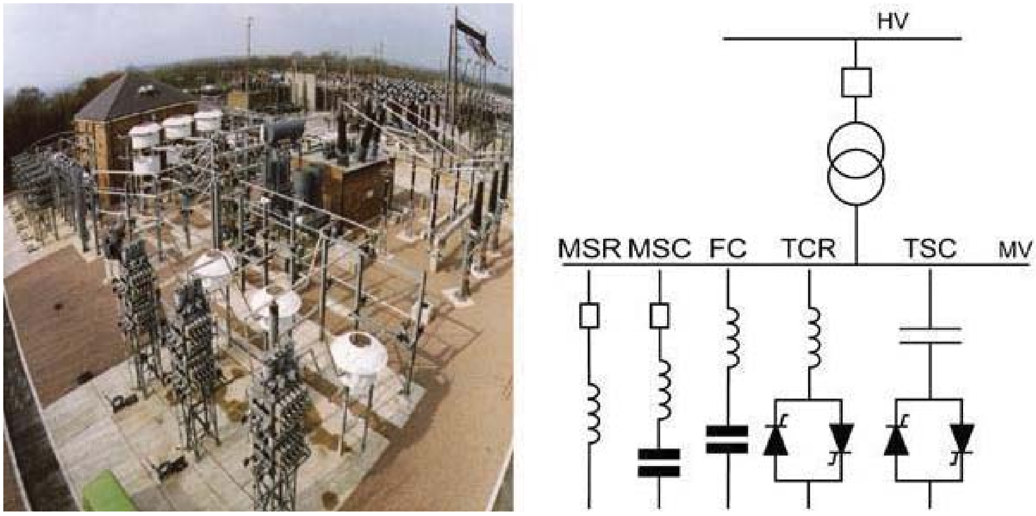


Figura 52 - SVC configurations [source: Alstom]

The typical V-I characteristic of SVC is showed in the following figure [67]:

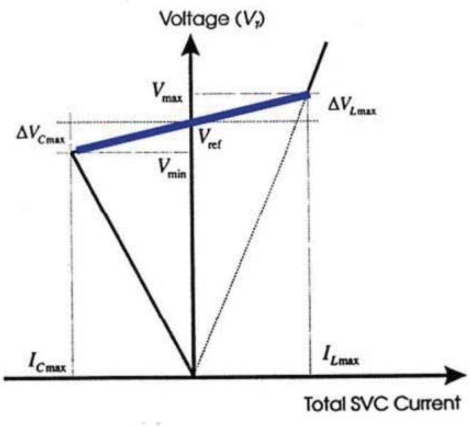


Figura 53 - SVC characteristic [source: ABB]

There are two different mode of compensation in SVC: step by step or continuous. In step by step way fixed capacitors or reactors banks are inserted or disconnected to the network by the action of switchgear (MSC/MSR Mechanically Switched Capacitors/Reactors), while continuous operation consents that the reactive power flow from/to the SVC is fully governed by thyristor-switched capacitors (TSCs) and thyristor-controlled reactors (TCRs). Filter branches (FC) can be supplemented as needed, both to compensate the harmonic generated by SVC power electronics or to reduce the effect of the other harmonic sources presents on the network (i.e. power electronics switching devices, non linear load).

The nominal voltage of SVC commercial systems is in the range: 52 ≤ kV ≤ 765, with control range: ~ 50 ≤ MVAr ≤ 1000 [66] .

Before the development of a reliable technology of capacitors and power electronics the ancillary service of reactive power compensation on HV grid had produced by rotating synchronous compensator, installed at strategic nodes of the networks.

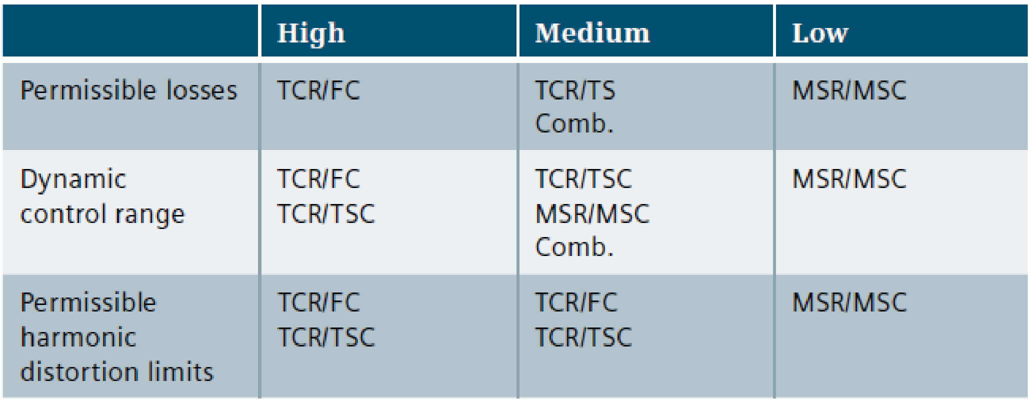
- MSC/MSR Mechanically Switched Capacitors/Reactors This is a step by step regulation of reactive power, actuated by means the insertion/disconnection of fixed capacity or inductance banks, operated with switchgear.
  (52 ≤ kV ≤ 765 ~ 50 ≤ MVAr ≤ 500) [66]
- MSCDN – Mechanically Switched Capacitor with Damping Network
  As a more highly developed form of mechanically switched capacitor, the MSC with an additional damping circuit provides essentially voltage support without increasing existing system harmonics:

Figure 54 - MSCDN [source: Alstom]

MSCDN provide a switchable source of reactive power to stabilize low frequency voltage variations.

- FC - Filter branches

Filters serve to absorb harmonics. Harmonics are whole multiples of the fundamental frequency (50 Hz/60 Hz) that are superimposed on it. Harmonics cause the system voltage to deviate periodically from the sinusoidal shape, resulting in voltage distortion. The number of filter branches and their resonance tuning frequency depend on the basic design of the Static VAR Compensator (SVC) and the harmonic distortions in the system. Harmonics are caused by devices with non-sinusoidal power input, including power converters, frequency converters, rectifiers and TCRs. A high harmonic content in the voltage of an electrical network can result in an unacceptable temperature rise in electric machines and a voltage increase in capacitor banks Which SCV configuration will be chosen depends on the application. Please see the following figures for details:



	High	Medium	Low
Permissible losses	TCR/FC	TCR/TS Comb.	MSR/MSC
Dynamic control range	TCR/FC TCR/TSC	TCR/TSC MSR/MSC Comb.	MSR/MSC
Permissible harmonic distortion limits	TCR/FC TCR/TSC	TCR/FC TCR/TSC	MSR/MSC

Figura 55 - Selecting the SVC [source: Siemens]

SVC for Wind

For off-shore wind or sea-energy generation, comprehensive AC sea cable networks call for additional elaborate reactive power control. The overall scope of reactive power control should encompass the wind farm just as well as the sea cables, to bring about a well regulated reactive power balance of the whole system, answering to the same demands on reactive power regulation as any other medium to large generator serving the grid.

STATCOM Static synchronous Compensator

Like SVC, Static synchronous Compensator STATCOM is a system used to compensate the reactive power in AC system. It is based on the voltage-sourced converter (VSC) technology [68].
A STATCOM can act the function of the SVC but with more dynamic and with less harmonics production. Moreover this systems, which converts the dc voltage storage into DC capacitors or battery, can also manage a portion of active power.

The following figure shows the simplest implementation of a STATCOM:

Figura 56 - Schematic diagram of a basic STATCOM [source: ABB (picture in the right: Alstom]

STATCOMs have a symmetrical rating with respect to inductive and capacitive reactive power.
The nominal voltage of STATCOM commercial systems is in the range: ≤ 52 kV ≤ 765, with control range: ~ 50 ≤ MVAr ≤ 500 [66].

B - Series Compensation

Series Compensation is an useful FACTS device, enabling stable transmission of large amounts of wind power from the generation site(s) to consumers over long distances [68].
Series compensation has been utilized for many years with excellent results in AC power transmission in a number of countries all over the world [69]. The usefulness of the concept can be demonstrated by the expression relating to active power transfer P over a transmission line between two nodes:

$P = U1U2\sin\psi / X$

U1 and U2 are the voltages at either end of the interconnection, whereas Ψ denotes the angular difference of the said voltages, and X is the transmission circuit reactance.

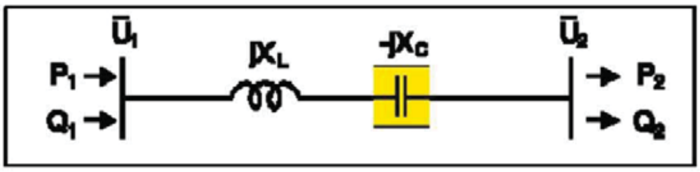


Figura 57 - Series compensated power transmission circuit [source: ABB]

From the above formula it is evident that the flow of active power can be increased by decreasing the effective series reactance of the line. In other words, if a reactance of opposite sign (i.e. a capacitive reactance) is introduced in the denominator, a corresponding increase in power transmission is enabled without having to increase the angular separation of the end voltages, i.e. with the angular stability of the link unimpeded.

Similarly it is demonstrated that by introducing a capacitive reactance in the denominator , it is possible to achieve a decrease of the angular separation with power transmission capability unaffected, i.e. an increase of the angular stability of the link.

The usefulness of series compensation in conjunction with offshore power can be expressed as follows:

- Enabling large amounts of wind power to be transmitted over large geographical distances with less overhead lines needed to be built than would otherwise be required
- In cases where wind power is to be connected to already existing grids, more room is made available in the grid for transmission of wind power under stable conditions.

FSC (Fixed Series Capacitors)

FSC are switchable banks of capacitors inserted in series with a line to compensate for the inductive voltage drop, effectively increasing the line length connection to the grid.

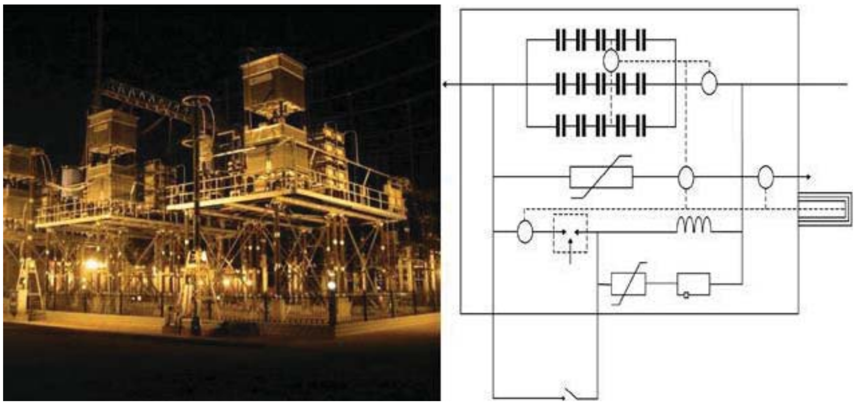


Figura 58 - FSC Series compensated power transmission circuit [source: Alstom]

TCSC (Thyristor Controlled Series Capacitors)

TCSCs are similar to FSCs but provide dynamic power flow controllability and can mitigate the effects of sub-synchronous resonance (SSR)

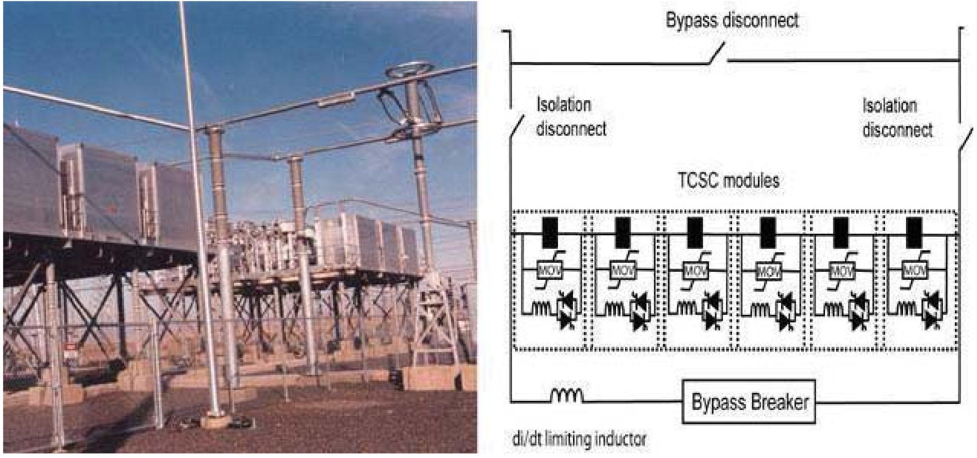


Figura 59 - TCSC Series compensated power transmission circuit [source: Alstom]

Application of TCSC for mitigation of subsynchronous resonance SSR [70].

The introduction of series compensation improves the transmission system behavior with respect to voltage stability and angular stability. However, under adverse conditions, at the same time electrical resonance might be introduced in the system.

Experience has shown that such electrical resonance may, under certain circumstances, interact with mechanical torsional resonances in turbine-generator shaft systems in thermal generating plants. This phenomenon is known as Subsynchronous Resonance (SSR). Today the SSR problem is well understood and taken into account when series compensation is planned and designed. Sometimes, however, SSR conditions may limit the degree of compensation wanted for better power system performance. The use of TCSC alleviates such restrictions.

4.3.2 GIS Gas Insulated Substations

The offshore installation suffers the impact of the harsh environment. With particular regard for the HV electric systems, the presence of salted moisture can reduce dramatically the dielectric capacity of the air exposed insulators and cause rapid corrosion on many metallic parts of traditional switchgear systems.

The best solution for offshore platform is the employs of Gas Insulated Switchgear GIS system, where all active parts of the electric system are enclosed on a SF6 gas atmosphere.

Figura 60 - GIS offshore substation (Alstom, at left) Indoor GIS substation (ABB Elk-3, right)

Moreover a GIS substation has a smaller footprint than a standard Air Insulated switchgear (AIS) system, and this is a most important issue for the installations over platform.

GIS Switchgear

Switchgear is equipment which allows switching to be performed to control power flows on the network. Switchgear comes in 2 predominant forms, Air Insulated switchgear (AIS) and Gas Insulated switchgear (GIS).

GIS is defined as ‘metal-enclosed switchgear in which the insulation is obtained, at least in part, by an insulating gas other than air at atmospheric pressure’. The insulating gas in GIS is sulphur hexafluoride (SF6) at a pressure of a few bars, which has excellent insulating properties and allows a more compact solution to be achieved compared to AIS.

The term switchgear encapsulates a variety of equipment including circuit-breakers, disconnectors, earthing switches and instrument transformers. In the case of AIS equipment this is typically stand alone whereas in GIS this is fully encapsulated within its earthed metallic enclosure.

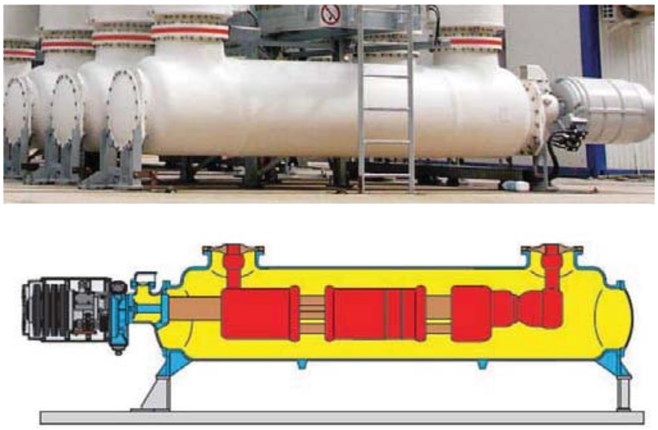


Figura 61 - GIS SF6 circuit breaker (ABB Elk-3)

One of the main benefits to having equipment enclosed is to protect against harsh environments. The insulating gas also allows the switchgear to be more compact and it is for these reasons GIS is typically installed in city locations and offshore where space is a premium. AIS equipment is typically installed in more rural and spacious areas.

The GIS substation European main supplier are ABB, Alstom Grid, Siemens.

The nominal voltage is up to AC 800 kV.

4.4 HVDC Systems

HVDC conversion is the process of taking alternating current (AC) power and converting it to direct current (DC) and vice versa. This has advantages onshore for very long transmission lines, due to reduced losses, but is increasingly also being use offshore due to the limitations on the length of traditional AC cables [55].

AC cables are affected by capacitive charging which limits the length that can be realistically used to about 70 – 100km. Efforts can be made to compensate for this effect but, even incorporating the increased cost of HVDC (converter stations etc), there is a breakeven point where HVDC transmission becomes the most appropriate option (see Figure below).

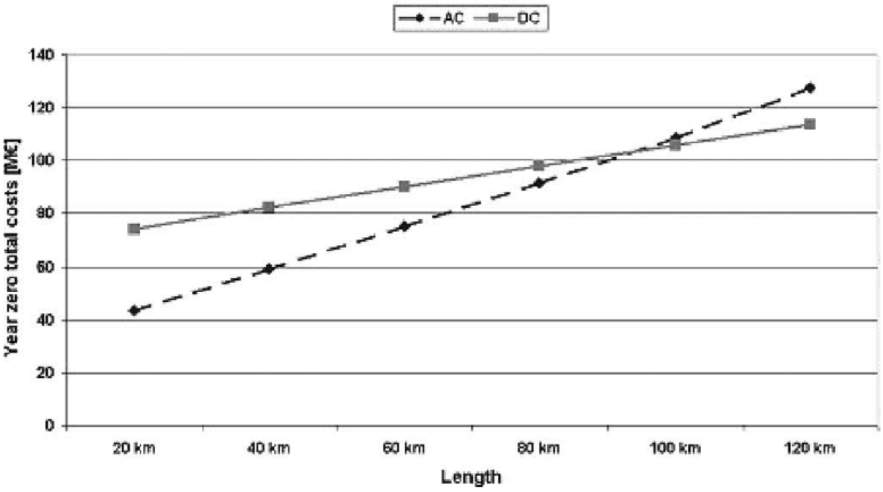


Figura 62 - HVAC and HVDC cost vs length of the power connection [source: Entso-e].

Large remote wind generation arrays require a collector system, reactive power support and outlet transmission.

Transmission for wind generation must often traverse scenic or environmentally sensitive areas or bodies of water. Many of the better wind sites with higher capacity factors are located offshore. Modern HVDC transmission not only allows efficient use of long distance land or submarine cables but also provides reactive support to the wind generation complex and interconnection point.

4.4.1 HVDC configuration

Monopolar HVDC Systems [71]

Monopolar HVDC systems have either ground return or metallic return. A Monopolar HVDC System with Ground Return consists of one or more six-pulse converter units in series or parallel at each end, a single conductor and return through the earth or sea. It can be a cost-effective solution for a HVDC cable transmission and/or the first stage of a bipolar scheme. At each end of the line, it requires an electrode line and a ground or sea electrode built for continuous operation.

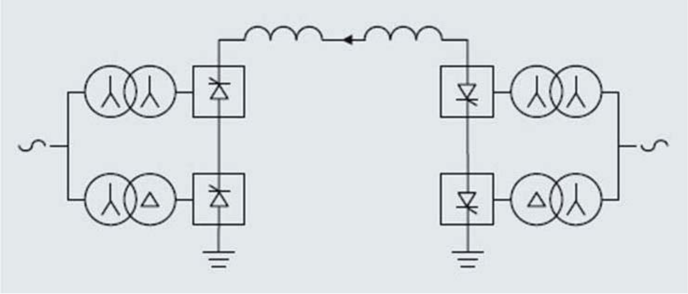


Figura 63 - HVDC monopole system with ground return [source: Alstom].

A Monopolar HVDC System with Metallic Return usually consists of one high voltage and one medium voltage conductor as shown in the following figure. A monopolar configuration is used either as the first stage of a bipolar scheme, avoiding ground currents, or when construction of electrode lines and ground electrodes results in an uneconomical solution due to a short distance or high value of earth resistivity.

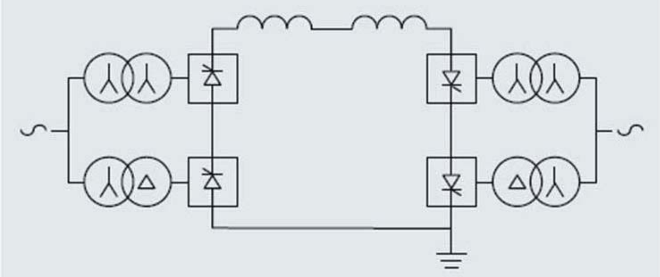


Figura 64 - HVDC monopole system with metallic return [source: Alstom].

Bipolar HVDC Systems

A Bipolar HVDC System consists of two poles, each of which includes one or more twelve-pulse converter units, in series or parallel. There are two conductors, one with positive and the other with negative polarity to ground for power flow in one direction.

For power flow in the other direction, the two conductors reverse their polarities. A Bipole system is a combination of two monopolar schemes with ground return, as shown. With both poles in operation, the imbalance current flow in the ground path can be held to a very low value.

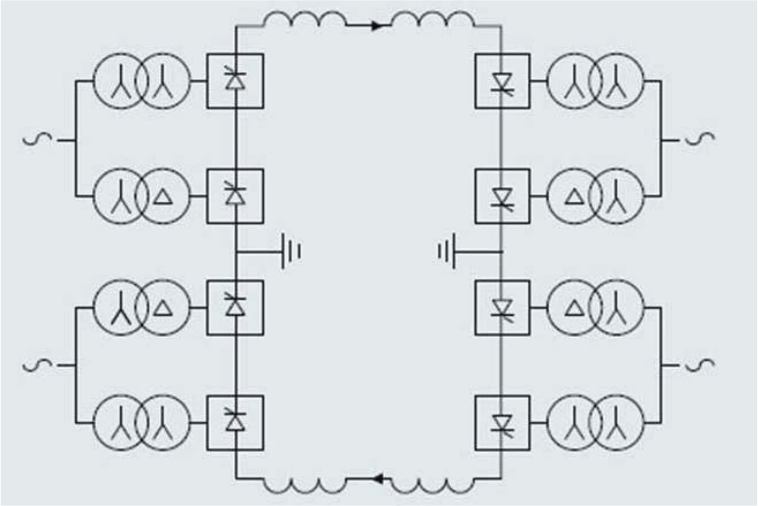


Figura 65 - Bipolar HVDC system [source: Alstom].

This is a very common arrangement with the following operational capabilities:

- During an outage of one pole, the other could be operated continuously with ground return.
- For a pole outage, in case long-term ground current flow is undesirable, the bipolar system could be operated in monopolar metallic return mode, if appropriate DC arrangements are provided, as shown in the following figure. Transfer of the current to the metallic path and back without interruption requires a Metallic Return Transfer Breaker (MRTB) and other special purpose switchgear in the ground path of one terminal. When a short interruption of power flow is permitted, such a breaker is not necessary.
- During maintenance of ground electrodes or electrode lines, operation is possible with connection of neutrals to the grounding grid of the terminals, with the imbalance current between the two poles held to a very low value.
- When one pole cannot be operated with full load current, the two poles of the bipolar scheme could be operated with different currents, as long as both ground electrodes are connected.
- In case of partial damage to DC line insulation, one or both poles could be continuously operated at reduced voltage.
- In place of ground return, a third conductor can be added end-to-end. This conductor carries unbalanced currents during bipolar operation and serves as the return path when a pole is out of service.

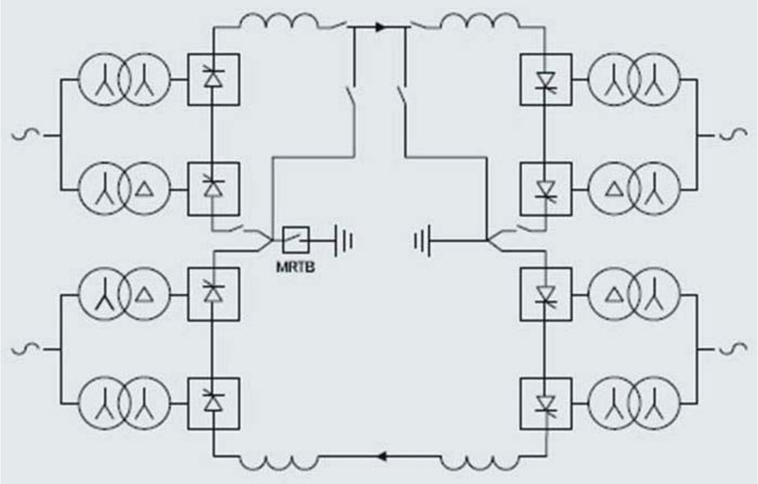


Figura 66 - Bipolar System with Monopolar Metallic Return for pole outage [source: Alstom].

Back-to-Back HVDC Links

Back-to-back HVDC links are special cases of monopolar HVDC interconnections, where there is no DC transmission line and both converters are located at the same site. The applications of back-to-back HVDC system consent the interconnection between two adjacent AC grids which can not be synchronized, i.e. having different frequency. They can also be used within a meshed grid in order to achieve a defined power flow.

Each converter is usually a twelve-pulse converter unit, and the valves for both converters may be located in one valve hall.

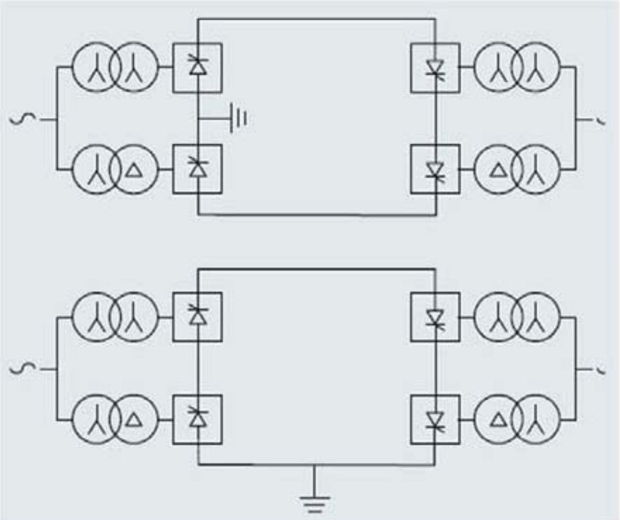


Figura 67 - HVDC Back-to-Back system [source: Alstom].

A large back-to-back HVDC system can comprise two or more independent links so that the loss of one converter unit will not cause loss of full power capability.

For very high power HVDC transmission especially at dc voltages above ± 500 kV, i.e., ± 600 kV or ± 800 kV, series-connected converters can be used to reduce the energy unavailability for individual converter outages or partial line insulation failure.

4.4.2 HVDC principles

A simple representation of a HVDC interconnection is shown in Figure 3.1. AC power is fed to a converter operating as a rectifier. The output of this rectifier is DC power, which is independent of the AC supply frequency and phase. The DC power is transmitted through a conduction medium; be it an overhead line, a cable or a short length of busbar and applied to the DC terminals of a second converter.

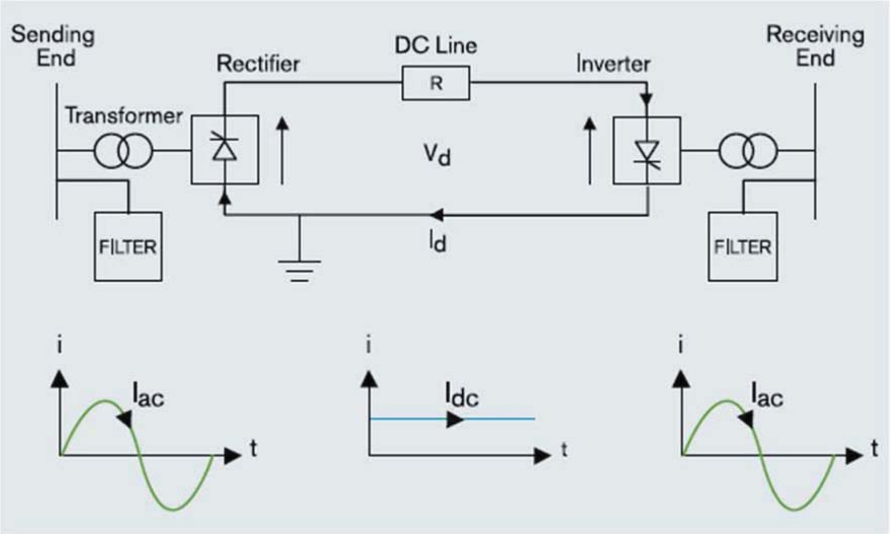


Figura 68 - Basic HVDC trasmission [source: Alstom].

This second converter is operated as a inverter and allows the DC power to flow into the receiving AC network.

Two types of HVDC systems are available, conventional thyristor-based Current Source or Line Commutated Converters (CSC/LCC), and the Voltage Source or Self Commutated Converters (VSC/SCC) systems.

Thyristors and CSC/LCC

The basic of HVDC LCC convertion systems is the fully controlled six-pulse bridge. The following figure shows the commutation sequence.

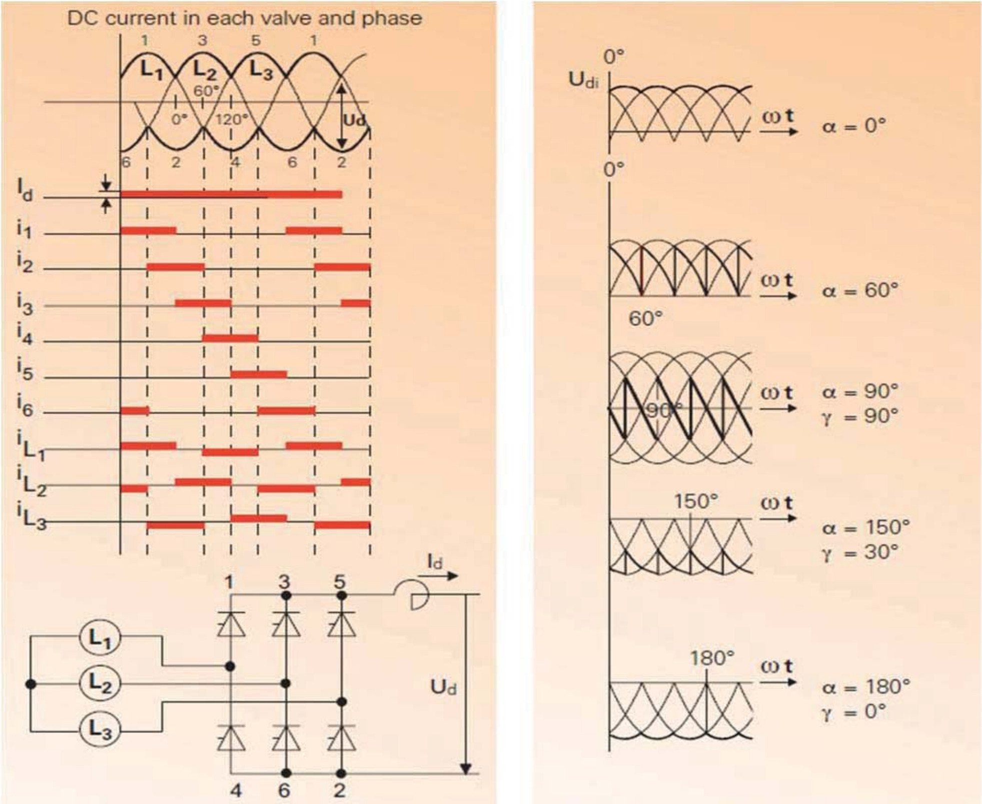


Figura 69 - Six pulse converter bridge [source: Siemens].

HVDC usually are built as 12-pulse circuit. This is a serial connection of two fully controlled 6-pulse bridges and requires two 3-phase systems which are spaced apart from each other by 30 electrical degree. The phase difference effected to cancel out the 6-pulse harmonics (order 6n +/-1, n=1,3,5 …) leaving only the characteristic twelve-pulse harmonics (12n □± 1, n = 1, 2, 3, ..) having more high frequencies than may be more easily reduced.

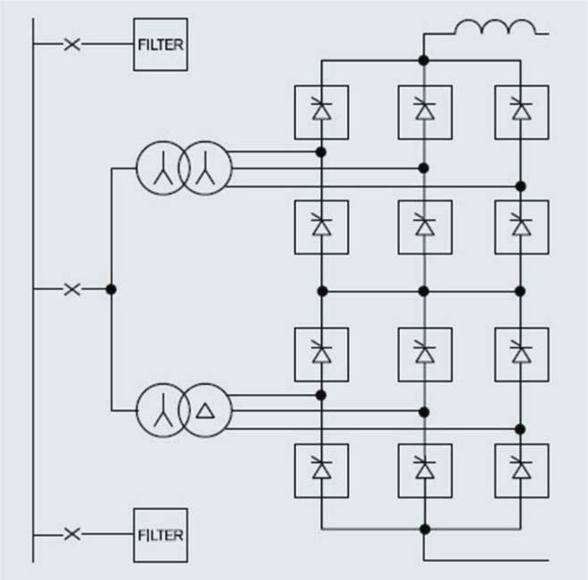


Figura 70 - Typical twelve-pulse HVDC bridge [source: Alstom].

Conventional HVDC transmission utilizes line-commutated thyristor technology. The following figure shows a simple thyristor circuit.

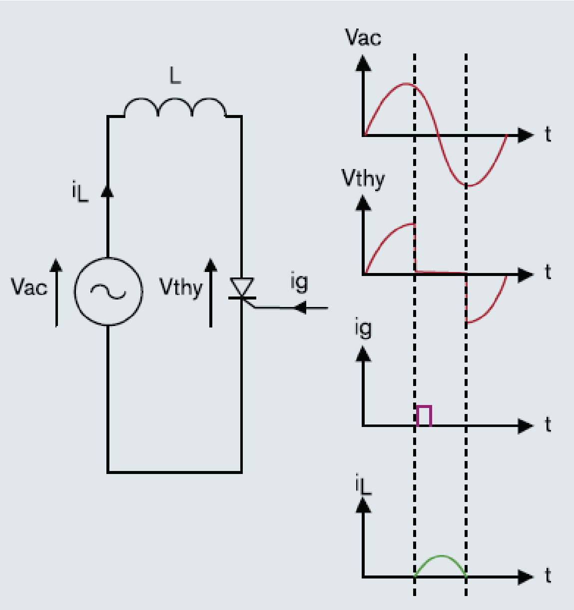


Figura 71 - Thyristor commutation [source: Alstom].

When a gate pulse (ig) is applied while positive forward voltage is imposed between the anode and cathode (Vthy), the thyristor will conduct current (iL). Conduction continues without further gate pulses as long as current flows in the forward direction.

Thyristor “turn-off” takes place only when the current tries to reverse. Hence, a thyristor converter requires an existing alternating AC voltage (Vac) in order to operate as an inverter. This is why the thyristor-based converter topology used in HVDC is known as a line-commutated converter (LCC).

IGBTs and VSC/SCC

Voltage-Sourced Converters require semiconductors which can carry current in both directions and withstand voltage in the positive direction. For such type of valve the state of the art is the employ of IGBTs: Insulated Gate Bipolar Transistors.

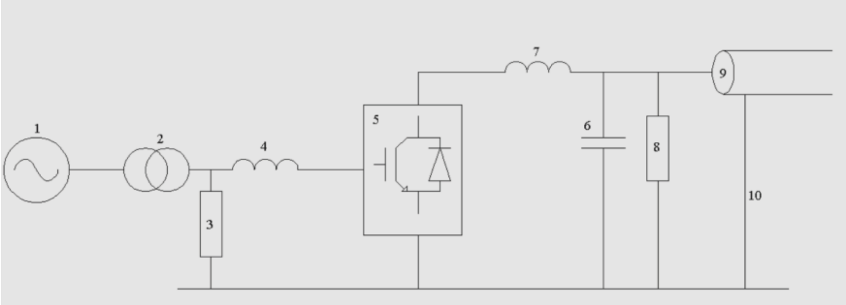


Figura 72 - VSC with IGBT valve arrangement

4.4.3 CSC LCC HVDC

A CSC LCC or classic HVDC system is based on thyristors as the switching element.

The name of the converter indicates the need of an existing AC network in order to achieve proper commutation. This converter operates with switching frequencies of 50–60 Hz and the power losses are 1–2%. This kind of transmission system can only transfer power between two (or more) active AC grids.

An auxiliary start-up system would be necessary if it would be used to connect an offshore renewable energy farm.

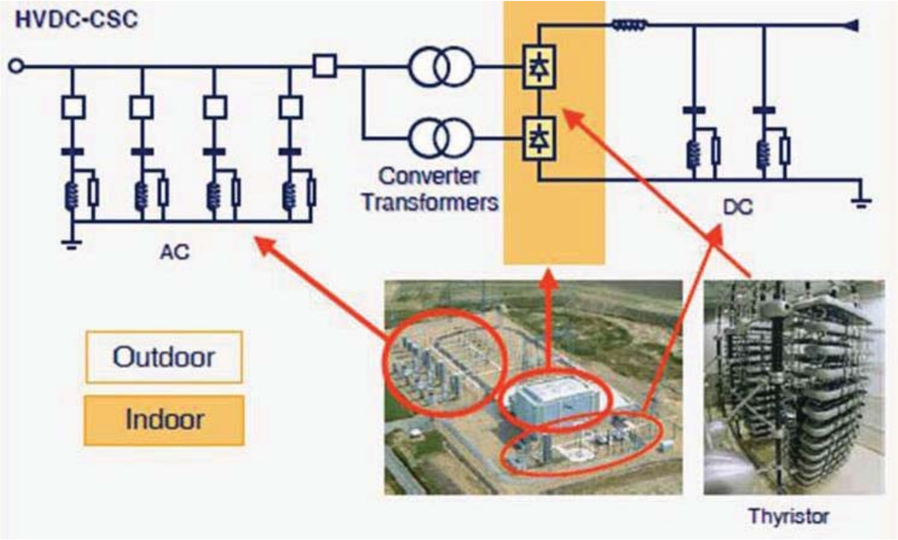


Figura 73 - HVDC LCC conventional transmission system [source: ABB].

Above figure shows a schema of a 12-pulse HVDC LCC transmission line. HVDC systems allow for instantaneous power control and there is no theoretical limit in the transmission distance unlike HVAC, since the distance is not limited by reactive power consumption of the cable [72].

HVDC LCC systems have the following main components at each end of the transmission line:

- Transformers.
- LCC converters based on thyristors.
- AC and DC voltage high harmonics filters.
- DC current inductors (DC current ripple).
- Capacitors or STATCOM for power compensation of the reactive required by the LCC converters.
- DC cables.

The basic building block used for CSC HVDC conversion is the three-phase, full-wave bridge referred to as a 6-pulse or Graetz bridge. The thyristor can be switched on by a gate signal and continues to conduct until the current through it reaches zero.

The term 6-pulse is due to six commutations or switching operations per period resulting in a characteristic harmonic ripple of 6 times the fundamental frequency in the dc output voltage.

Each 6-pulse bridge is comprised of 6 controlled switching elements or thyristor valves. Each valve is comprised of a suitable number of series-connected thyristors to achieve the desired dc voltage rating.

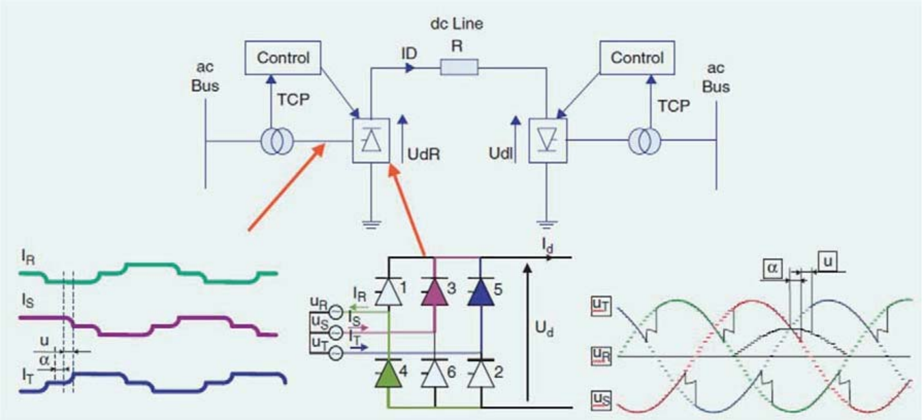


Figura 74 - HVDC CSC commutation scheme [source: ABB].

The dc terminals of two 6-pulse bridges with ac voltage sources phase displaced by 30 degrees can be connected in series to increase the dc voltage and eliminate some of the characteristic ac current and dc voltage harmonics. Operation in this manner is referred to as 12-pulse operation. In 12-pulse operation the characteristic ac current and dc voltage harmonics have frequencies of 12n ± 1 and 12n respectively. The 30 degree phase displacement is achieved by feeding one bridge through a transformer with a wye-connected secondary and the other bridge through a transformer with a delta connected secondary.

Most modern HVDC transmission schemes utilize 12-pulse converters to reduce the harmonic filtering requirements required for 6-pulse operation, e.g., 5th and 7th on the ac side and 6th on the dc side. This is because, although these harmonic currents still flow through the valves and the transformer windings, they are 180 degrees out of phase and cancel out on the primary side of the converter transformer.

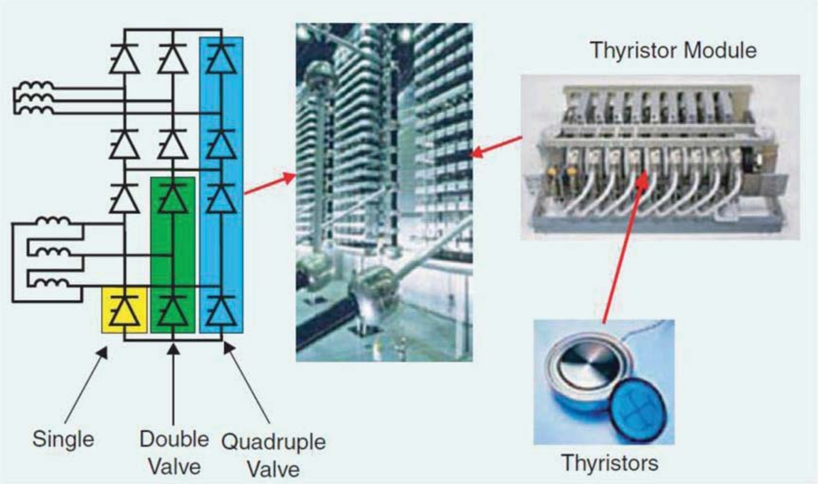


Figura 75 - HVDC thyristor valve 12-pulse arrangement [source: ABB].

Above figure shows the thyristor valve arrangement for a 12 pulse converter with three quadruple valves, one for each phase. Each thyristor valve is built up with series-connected thyristor modules.

Line-commutated converters require a relatively strong synchronous voltage source in order to commutate. Commutation is the transfer of current from one phase to another in a synchronized firing sequence of the thyristor valves.

The three phase symmetrical short circuit capacity available from the network at the converter connection point should be at least twice the converter rating for converter operation. Line-commutated current source converters can only operate with the ac current lagging the voltage so the conversion process demands reactive power.

4.4.4 SCC VSC HVDC

Advances in improving the performance of self-commutated semiconductor devices have led to Self Commutated – Voltage Source Converters SCC VSC HVDC, commercially available as HVDC-Light (ABB), HVDC-Plus (Siemens) and MaxSine (Alstom Grid). The VSC converters normally use insulated gate bipolar transistor (IGBTs) as valve and allow independent control of both active and reactive current.

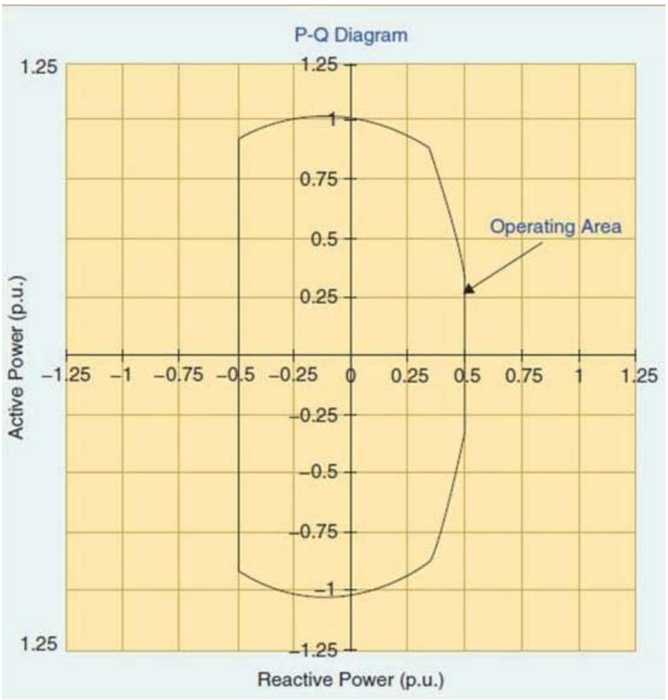


Figura 76 - HVDC VSC operating range [source: ABB].

- Transformers.
- VSC HVDC converters (one offshore and one onshore).
- AC and DC filters.
- DC link capacitors.
- DC cables.

The following figure shows the basic layout of VSC system.

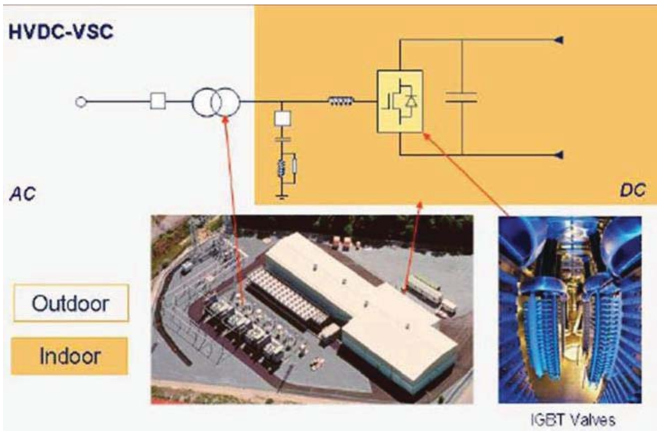


Figura 77 - HVDC VSC layout [source: ABB].

VSC HVDC has several advantages over conventional LCC HVDC in offshore applications. It is more compact and more flexible due to the reactive power capabilities. Also, it does not require an active AC grid for commutation at the offshore end (self-commutated switches).

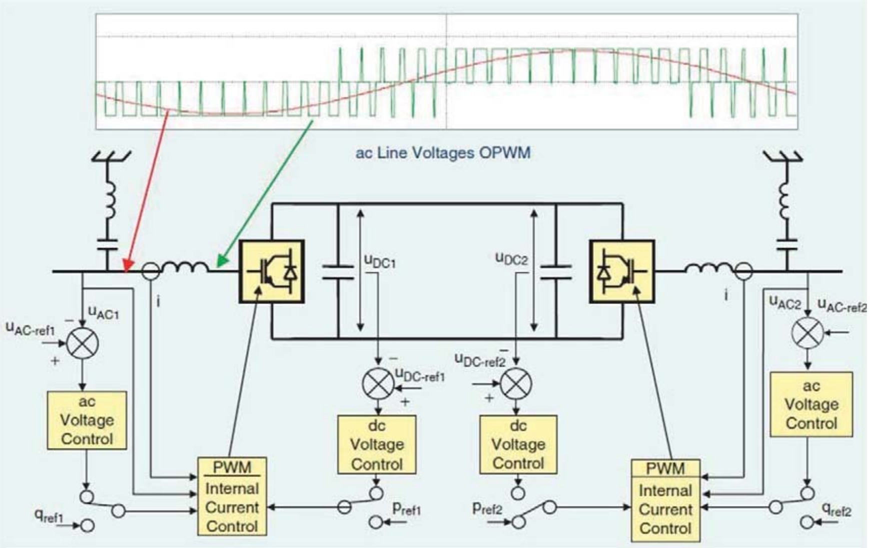


Figura 78 - HVDC VSC PWM control [source: ABB].

The previous figure shows the typical Pulse Width Modulation PWM control scheme of a VSC converter.

Moreover, this transmission system, HVDC VSC, allows a total and independent control of the active and reactive power at each line end. In this way the injected power can be controlled with large flexibility. This is very useful in order to obtain a better power quality and to keep the grid stable.

The losses in conventional HVDC including the converter transformer losses are about 1% per converter station. The corresponding converter losses for a 150 kV VSC converter and transformer are on average 3% per converter station. (about 2% for converter and 1% for transformer). The losses from the VSC converters are relatively high due to the high switching frequency of the semiconductors. However, the high frequency commutation reduces the harmonics, and thus the number of the filters is reduced compared to the LCC converters.

Commercial systems are available with power between 50 and 1.100 MW, with voltages up to ±300 kV. The first HVDC VSC System was installed in 1997 in Hellsjon by ABB, with a power rating of 3 MW and 10 kV voltage with the goal of studying the

viability of the technology. During the last ten years several systems have been built, including submarine transmission lines.

The Troll gas extraction offshore platform uses a VSC converter with rated power of 80 MW, the transmission distance of 68 km and the voltage is ±60 kV.

Figura 79 - VSC power supply to Troll A production platform [source: ABB].

VSC converters can start-up with a dead grid, thus no additional start-up system is necessary offshore. Even when the onshore grid has collapsed, the system may start by itself.

4.4.5 Other operation aspects HVDC versus HVAC

Transmission capabilities HVAC transmission using high voltage submarine cables is impractical in case of long distances. Due to the cable capacitance the charging currents become excessive. Secondly, it requires a large amount of reactive power compensation. Intermediate compensation without building platforms, i.e. seabed placed sealed inductors, have not been developed yet.

Losses

In HVAC systems relative losses depend on the distance (i.e. the cable length), the cable voltage and the cable design (conductor resistance, dielectric loss factor, shield currents, skin effect, and shield resistance). Depending on the system type, the system losses become over 10% in case of distances > 100 km.

The losses in HVDC systems are strongly determined by converter losses; globally 1.5% per converter. In HVDC system losses are mentioned:

- VSC HVDC: typical 4 - 6 %
- LCC HVDC: typical 2.5 – 4.5 %.

Cables

The weight of the cables is an important aspect. For example a transmission system;

rated at 550 MW over 75 km distance needs HVDC cables with a specific weight being only 40% of the weight when applying an HVAC system. Important to mention is that AC needs 3 cables and DC only 2 (bipolar). This aspect brings an important advantage related to cost of the cables and the deployment cost. Reliability DC system uses a large number of complex components (converters, valves, filters, reactors) that are connected in series. The system availability can be approved by redundancy. But the extra availability must be balanced with the extra costs. Splitting up the power to be transported over multiple connections will also result in a significant reduction of the system non-availability. Availability data from the Sweden – Poland 600 MW HVDC connection shows an average availability of 93% during 9 years. The availability was over 98% during 4 years. Two times the system failed due to reactor fire.

5 INSTALLATION AND O&M ASPECTS

Renewable offshore energy sector is expected to use large open marine areas near coasts to install multiple power plants; these plants are inevitably characterized by the presence of offshore structures to support wind turbine and other electrical equipment, subsea structures and moorings to support tidal, current and wave generators and converters, requiring all to be designed for operation in an harsh environment that is well known by the offshore oil & gas industry. Since the oil & gas industry has been operating in the marine environment for a significant period it has lead to advances in vessel design, systems design and operating standards developed to meet the ever increasing water depths of operation (up to 3,000 meters and above). Also the renewable offshore energy sector is moving further away from shore and deeper waters: obviously the increasing water depths pose challenges in designing structures, power cables and subsea electrical component to be used specially related to the fact that:

- to reach the seabed there is the need for larger offshore structures and then of larger surface equipment their installation,
- to lift and lower objects to the seabed larger crane handling capability is required,
- there is the need to use larger vessels to hold the increased weight and length of requested structures and cable.

The oil & gas industry can offer a rich set of marine assets capable of providing required services to the offshore renewable energy industry, such as:

- Tugs & barges for shore landing services and transport services of offshore pieces.
- Heavy lift capable vessels for handling and installing offshore structures, deployment of generator assemblies and associated piece parts.
- Cable lay capable vessels for laying and burial of power cables in the collection and transmission system
- Sub-sea capable vessels with Remotely Operated Vehicles or diving assets to perform inspection services of the subsea elements.

All of the above vessels are available but it’s important to choose the right type according the particular site of installation and activity to be performed. For example, there are offshore construction vessels or OCVs representing the choice of excellence for deepwater installation work, characterized by large deck space for mobilization of a variety of equipment and other resources depending on job requirements (minimum 800m2), multiple crane capability, accommodation for people, subsea reference and positioning capability; for all these feature the daily rate is very high [44]. For installation in shallow waters can be generally used smaller and less costly marine assets, having daily rates about of the half of the previous OVC [44].

For installation activities relevant to an offshore power plant it can be useful to break up the work load and spread it across different specialty assets that will be mobilized and utilized at the right phases, rather than mobilize a single asset capable of performing all the activities. For instance, a tug & barge can be the right asset for installation services since it can be utilized for moving materials to and from shore and worksite; it can be utilized for near shore installation of cables too.

To secure a barge there is the need to another vessel to get tied or of a 3-4 points anchoring system. Jack-up lift boats are suited for heavy lift then for structure and generator packages installation.

Cable laying and correlated activities like burial are the most specialized part of the installation. Handling machinery for cable installations is not easily or readily available to the industry as stand-alone equipment, in fact most of them is contained within cable laying vessels. Cable laying vessels are generally large marine assets of 110 meters or larger and are expressly designed to store large amount of cable and redundant machinery handling systems. For these reasons they are expensive and not easily available.

As further described in the following paragraph cable protection, like for instance burial, can be performed during installation, using typically a cable burial plough, or afterwards by using an ROV generally equipped with a cable jetting tool. In the first case, as plough are big, large handling equipment is required for launch and recovery actions while ROVs, being smaller units, can be easily put onboard a generic vessel.

Inspection and installation activities in shallow waters (20-50m) can be also performed by divers that are generally used for near shore cable installation services such as cable landing services, post lay inspection and cable protection.

Installation activities in the offshore renewable energy sector strongly depends on the type of primary source to be converted; for what concern connection to the grid related activities it is important to underline that for wave and tidal power plants, located in sea areas where a particular dynamic environment exists, the use of particular assets capable of withstanding typical high currents or high swells and sea state is required. Motion between the generator systems and the cable connection is a key risk area and burial of cable in high current areas may not be possible due to the scouring (erosion) effect of the high currents on the seabed.

5.1 Site survey and desktop study

A mandatory base for performing any offshore installation activities and to properly design subsea structures and devices according to operation conditions, is constituted by a marine route and site survey through which a series of data and important information about bathymetry, the nature, geophysical characteristics and morphology of seabed and layers below seabed, sediment movements, sensible natural resources and hydrological conditions can be achieved. These are useful to understand, for example seabed preparation actions to be undertaken referring to structures to be installed, particular installation techniques and procedures to be preferred, existing cables and pipelines or other subsea obstacles or areas to be avoided.

The marine route and site survey has to cover the entire field of installation from the energy farm located offshore to the shore landing areas. This type of service are supplied by specialized companies that use special marine assets and can offer also a so called Desk Top Study (DTS) through which a large amount of data can be retrieved from public sources, marine authorities, seabed and sea users, bathymetric charts, marine soil maps, mainly without leaving the office. Output of a DTS can be for example permitting environmental conditions, current and tidal conditions, weather conditions, fishing activities, that constitute a sort of preliminary information also to plan the site survey.

5.2 Installation, protection and O&M of submarine cables

Cable installation can be conducted in different ways: they can be laid by a cable laying vessel and subsequently buried using a separated vessel with trenching/jetting equipment, or can be simultaneously laid and buried with burial equipment directly towed by cable laying vessel or barge, or operated from a vessel in case of a self propelled ROV. Another, not easy to implement method, is characterized by the use of a separate vessel to open a pre-cut trench where the cable is put during laying. The method to chose depend on site specific condition and a multitude of factors, including cable type.

A part of installation activities regards the routing of cable from the seabed, up the side of the energy converter structure or platform for termination. Attachment of the cable must be carefully designed to support cable weight and environmental forces to which it is subjected: hang-off devices support suspended cable allowing the possibility to secure it to the side of the structure.

In case power extracted by inter array cables is collected by a sub-sea sub-station or junction box, cables connections can take place with existing connectors technologies already described in the previous chapters.

Installation of array and export cables in wave and tidal energy farms can be very problematic due to the energetic environment by which they are characterized that is usually accompanied by hard scoured seabed conditions. To date moored barges and multi-purpose vessels have been chosen for cable related activities.

Landing of subsea cables usually represent the most demanding part in terms of engineering, equipment an time of a cable project and usually constitute the starting phase of laying activities. It is strongly dependent by shore condition so different methods have been developed. Sometimes it is possible to open a trench through the beach in other cases closed pipes are the only solution to be chosen. In the first cases the open trench starting from the sea entrance arrive at the beach joints that fixes the transition between subsea cable and land cable. The trench must be as straight and possible and designed according to thermal stresses acceptable by the cable. In the latter cases horizontal directional drilling (HDD) is the preferred method in which a drilling station is erected and drills a hole with a predetermined curvature under the ground, with the possibilities of controlling the path in all directions. Cables are then pulled-in in the hole once it has been lined with steel or plastic welded sections of pipe.

When a cable comes ashore it may be suspended by floats and guided into position by small boats and divers. Floats are detached or deflated and the cable is placed in its final position determined by the route survey, with the possible help of divers in very shallow water.

Divers may be used to assist installation operation in general in shallow water while deep water laying may involve Remotely Operated Vehicles (ROVs).

Cable laying vessels (CLV) are available in a wide range of sizes and onboard equipment even with more than 6000t turntables and capable to operate in heavy sea state conditions. High capacity vessels are not a lot and so they are available with considerable day rate. Other vessel types can be temporarily converted for cable laying purposes. By tradition cable installation and maintenance has been realized with multi point anchored barges with or without self propulsion for relatively shallow waters applications and self propelled deep-water vessels: the 1980s see the introduction of dynamic positioning as station keeping mode and from that day this method is the established one for cable installation and repair works. Another technology that, respect to the past, has enhanced accuracy and repeatability in knowing where a cable or other subsea asset is placed for initial correct localization and subsequent interventions is Global Positioning System (GPS). For cable laying purposes load carrying capability, maneuverability, deck space for cable handling equipment and jointing house, necessary personnel, sea-keeping properties are factors to be considered when choosing a cable laying asset.

Load capacity is important considering that it is important to reduce the number of costly and riskily joints at sea. Turntables are used to store cable on board without bending it too much, they can be featured with an inner and outer partition and some vessel can have more than one (typically two) turntables on board. For projects characterized by short cable lengths, as for example inter array connections in offshore wind farms (400-800m) barges with cable drums can be used instead of a CLV.

The jointing o submarine power cable is a complex operation requiring specially equipped jointing houses with electric power supply, air condition and dryer. Cables tensioner or linear machines are necessary for moving cables on board and applying the correct tension when laying. Also emergency cutters are important features needed for example when extreme weather conditions impose cutting the cable in a short time (60-90s). Other necessary elements like chutes, laying wheels and arms, pick-up arms, rollers are important to be chosen in accordance with project data in order to assure effective and safe installation. Many laying related activities can be performed only with ROV, equipped with a wide range of manipulators and tools: if foreseen, the laying asset must have adequate space and equipment for its launch and recovery. Helicopter pad can be another feature for application in which other means of personnel transport is not possible.

When cable are shipped in long coils on turntables the need lengths are cut on site: it's important to properly seal ends to avoid damages related to humidity and water intrusion, and hence the need of extra spare cable and joints. Even if modern laying cable vessels have the capability of storing and handling considerable lengths of cable, the necessity of make joints at sea it is unavoidable. The deployment of a manufactured joint is a complicated operation since two parts of cables must be handled simultaneously with the joint: several possibilities for joints realization are available, generally referred as in line joints (where a first part of cable is laid then the joint is made onboard, picking up the already installed cable and connecting by the joint with the second part of cable to be laid), after installation joints (where the two parts of cable are both laid with a overlap and their jointing is made afterwards on a vessel picking up the two cable ends).

Submarine cables represent a precious component of an offshore project so they need to be adequately protected from hazards and hostile seabed interventions: from a Cigre study of 1986 principal faults and protection methods can be evaluated. Cable protection can be achieved selecting a suitable cable route, designing a proper armour according to installation and operation conditions, using external protection system directly on the seabed, and installing after installation protection systems.

Safe installation and protection techniques for subsea cables were initially developed by the telecommunication industry and starting from the early 1980s cable burial became the principal method to achieve protection. Early research studies on the matter showed that the confidence in protection increase significantly with depth of burial and that addition of a cover protection helps preventing from external action related cable faults, in case of open trenches.

In recent times, to choose the most adequate burial depth, considering also economic aspects, the use of a risk based approach using a Burial Protection Index has been extensively adopted: this method consider both site specific soil conditions and threat level posed by third party interaction (fishing gears, ships anchors, dredging).

According to this cable different subsea ploughs and specialized burial equipment have been developed, with incorporated instrumentation and control features, together with remotely operated vehicles (ROVs) and free swimming ROVs suitable to projects characterized by quite short lengths of cable burial, shallow water applications or whenever ground conditions are not compatible with conventional subsea plough and specialist cutting tools are required.

The offshore wind sector has set typical target burial depths comprised between 1m and 2m but, as the industry is moving into deeper water, cable risk assessment may identify the need for increased burial depths in order to consider the possibility of anchor damage from larger seagoing vessels. Various cables in the same area are typically buried some distance apart from each other to allow for safe maintenance.

Even selecting the best cable plough machine reaching the desired cable depth of burial is not always achievable since unforeseen events like for example extreme weather and or ground

condition, equipment failure may occur; in this case remedial measure are required, that can consist in post lay burial or alternative protection methodologies compatible with seabed characteristics.
According to [45] cable burial machines family have been decided to be divided in:

- Cable Burial Ploughs;
- Tracked Cable Burial Machines;
- Free Swimming ROVs with Cable Burial Capability;
- Burial Sleds.

To the first class belong conventional narrow share cable ploughs, advanced cable ploughs, modular cable ploughs, rock ripping ploughs, vibrating share ploughs. Cable ploughs are towed from the host vessel and allow that the cable is simultaneously laid and buried: their operation is characterized by lift of a wedge of soil, placement of the cable at the base of the trench before the wedge of soil, via gravity, backfills over the cable. These devices can work with different soil types in shallow waters and water depth up to 1500m.
Tracked cable burial machines can be equipped with different burial tools such as jetting systems, rock wheel cutters, chain excavators, dredging systems. They are generally operated and controlled by means of an umbilical cable from a host vessel such as a Dive Support Vessel (DSV) or a barge. They usually operate once the cable has been already laid and the selection of the proper burial tool to be equipped with is selected depending on foreseen seabed conditions. They are used with short lengths of cable to be buried and with the help of divers that assist loading and unloading of cable if a dedicated automatic system is not provided. Typical application are shallow waters and water depths to 2000m.
Free swimming ROVs can be equipped with jetting systems and dredging systems for cable burial and similarly to the previous group of ploughs, are operated and controlled from a host vessel such as a DSV or a barge. They work after the cable is laid in sands and clays, with short length of cables, from 10m up to 2500m water depths.
Burial sleds can be equipped with jetting systems, rock wheel cutters, chain excavators, dredging systems and usually work in ports, estuaries, river crossings and shore-ends for cable systems. They are often deployed from barges or jack-ups and they need power supply from dedicated power modules or from the host vessel: they are suitable for sands, gravels, clays and softer rock seabed conditions

Cable plough

Tracked Cable Burial Machine

swimming ROV

Figure 80 - Example of burial equipment [45]

Cable ploughs seems to be the preferable choice for export cable routes since the lengths of cable are more suited to the burial method while tracked cable burial machines e burial machines seems more likely to be employed for inter array cables than for export ones even if possible: the particular type to choose always depends on specific seabed conditions (e.g. jetting systems are to be used in sandy and soft clay seabed on the contrary mechanical cutting tools have more possibilities of application).

Free swimming ROVs having cable burial features are common in deeper water application and for repair intervention purposes. Burial sleds, typically used in shallow waters and requiring diver assistance for the loading and unloading of cable, can be a good choice for the shore section of export cable.

Cable burial for offshore wind farms is usually undertaken using a barge equipped with cable handling and burial apparatus and a number of heavy duty tow winches to provide an adequate anchor system for achieving stability during cable burial operations.

Export cables from an offshore wind farm are installed within a cable corridor, that may be in general 500m to 600m wide of the central line of the planned cable route that gives the possibility to avoid any localized obstructions (e.g. wrecks) discovered for the first time in the site specific survey and areas of difficult ground conditions (e.g. rock outcrops) or mobile sebaeds.

When cable burial is not feasible both for seabed/sea state and operational reasons alternative protection systems and methodologies can be implemented, accurately evaluating the specific location. Typical examples of application are offered by:

● parts of cable comprised between J/I-tubes and transition point where the cable is initially buried (about 10m to 20m away from the J/I-tube);
● subsea cables crossings with existing cables or pipelines;
● areas of surface laid cable due to special contingencies or seabed conditions.

In the group of alternative or after installation methods we can find: concrete or cement mattresses/bags/slabs, rock dumping, grout bags or sand bags, frond
mattresses, uraduct, articulated metal shell connectors (cast iron half pipes), directional drilling.

Concrete mattresses are extensively used on power cable and pipeline installations as principal protection as well as for crossings over other existing subsea cables and pipelines. They consists of blocks connected by polypropylene rope and are prefabricated. They are transported on site by a vessel and can be automatically applied from the sea level; for ensuring the correct placement a diver is usually requested. For some projects requiring the cover of long lengths also ROVs have been
developed. Different sizes, weights and densities of the concrete are available but they have to be chosen according to stability calculations which have to consider any potential scour effects around the mattresses. At crossings generally the cable will be contained within two mattresses layers as in a sandwich. Apart from cable protection concrete mattresses are also used for stabilization, scour prevention, support purposes

Rock dumping can be applied along cable length as well as at crossings with subsea existing elements. In shallower waters it can be achieved using side tipping vessels or a grab device.

Grout or sand bags can be regarded as a smaller scale version of the already described mattresses. Their installation usually sees the presence of divers to fix and stabilize the placement on cable. They can be of pre-filled or empty fabric type: in this case they arrive on the seabed and a diver coordinate their filling with provision of material needed from a vessel.

Frond mattresses are used to increase protective cover on a surface laid section of cable through stimulation of the deposition of water suspended/transported sediments. The sediments, at contact with frond, are forced to settle forming new sand banks: the appropriateness of this technique have to be accurately evaluated.

They can be installed like concrete mattresses.

Frond mattresses are also use as anti-scour protection for subsea structure and pipelines, since they act as natural seaweed capable of reducing water velocity and then scour.

Uraduct protection systems comprise two cylindrical half shells which form close fitting protection around the cable, umbilical, or flexible/rigid flowline. They are manufactured using high performance polyurethane elastomer and typically in lengths of up to 2.0 m each half. Their flexing characteristics have to be compatible with required minimum bend radius of the product or ancillary shipboard lay equipment.

Various sizes and stiffness capabilities are available to adapt to special product and different impacts: they are used for crossings protection or in areas close to structures to protect from objects fallings.

Articulated metal shell connectors are used whenever there is the need to provide added mass and enhance abrasion resistance to certain cable sections as in high energy environments like shore landings, which pass over rock outcrops and where other forms of cable burial are not possible. They are applied by divers.

Directional drilling is employed where is difficult to achieve conventional trenching or where there are environmental interesting zones to avoid since it allow to have a localized, temporary disruption, bypassing critical areas.

Particular attention have to be paid in case of mobile seabed. It may happen that originally surface laid sections of cable have been found covered by sand and vice versa. A technique is to increase burial depth but this is effective only with relatively low sand waves (about 1-1.5m). To mitigate the effects of mobile sediment seabeds, the best solution is to plan the cable route to avoid these areas according to data deriving from site survey and desktop study.

It may also happen that export cables have to cross existing or proposed navigable channels: commonly the export cable can be installed once the navigable channel has been already pre-excavated or without any pre-excavation activity by using subsea plough or trenching vehicles equipped with a deep burial plough share or cutting tool.

Another challenge is offered by rocks: if they are encountered at a cable landing zone, horizontal directional drilling would be the preferred cable protection method, while offshore, rock ripping plough, rock wheel cutter or a vibratory share plough would can be used.

Once a cable is installed, the protection can be maintained and improved by after installation active measures. Beach warning signposts, notification on sea charts and to marine authorities, fishermen and related organization, synthetically information to people, is important since the majority of cable damages are caused by human activities. Beacons are permanent and directly visible warnings, usable onshore and are especially useful whenever vessels come close to shore (e.g. fiords): they can also show the direction of cable from the cost.

Buoys are also used in special circumstances to provisionally mark a cable route for short periods of time, for example during repair or maintenance activities. A further way of post-installation protection is constituted by monitoring of ship movements close to cable routes.

Periodical inspection surveys of the inter array and export cables are generally carried out from which cable repair and remedial cable protection activities can result [8]. Suitable instrumentation and methods comprising Distribute Temperature Measurement Systems (DTS) for monitoring the temperature inside the cable, Cable Dependent Voltage Control (CDVC) which is a control function resident in HVDC converter station, designed for DC mass impregnated cables, that allows the temporary reduction of voltage level at reduction of power demand, Partial Discharge (PD) monitoring to detect cable defects and specialized ROVs are available. Solid cables (mass-impregnated and extruded) and relative joints are maintenance free: in case of terminations in Gas Insulated System (GIS) terminations, having these a small amount of insulation oil, level/pressure monitoring is required. Generally for harsh environment of installation insulators must be regularly checked and cleaned from salt deposit and all termination must be checked for corrosion.

Repair of damaged power cables require specialist ships and cable jointing experts to replace the damaged section and the completion of this activity can take a few days as well as a few weeks, depending on the extent of the damage, location of the fault, time needed to mobilize a suitably equipped ship, weather conditions.

For repair, replacement or other activities on inter array, “in service” cables vessel with dynamic positioning features are preferred (to avoid anchors).

To repair an inter array cable, for space reasons and short lengths involved cable replacement is generally preferred respect to a jointing operation. For export cable repairs jointing is the most likely option to adopt. Either for replacement and joints adequate spare cable is needed: repair vessels may differ a lot from laying vessels since spare cables and related handling equipment are characterized by smaller figures compared to the ones involved in installation/laying campaigns. There are no standard rules for cable repair operations: firstly it’s important to establish fault location and for this task several methods are available like:

- Time Domain Reflectometry (TDR) in which an impulse travels along the cabl until it reaches the cable break,
- bridge measurements, based on resistance measurement from one cable end to fault, using variations of resistance bridges,
- fine localization that uses a search coil onshore a vessel to measure differences in magnetic field around the cable length cause by current injection from shore and provide precise fault detection.

Other methods involve the use of fault recorders of substations located at cable extremities, measurement of complex impedance at varying frequencies, galvanic effect based methods (for which a DC current is injected in a damaged cable core and for a galvanic reaction, gas bubbles observable by a ROV are produced).

ROV mounted equipment is very often used to confirm cable fault localization, so deburial and cutting of cable at the seabed are logical subsequent activities demanded to ROVs otherwise, depending on particular site condition other grappling method/equipment can be used.

As already stated above cables can be damaged by human activities (fishing equipments, anchors, hits of ships); other types of damages are installation damages (related to loss of DP by the laying vessel, not proper cable loading/de-loading, emergency cutting, kinks due to not good coordination of CLV progression and cable pay-out) spontaneous or internal damages (related to lifetime of cable insulation and ageing, fatigue, water intrusion effects), failures of joints (for inadequate design or assembly), damages related to oscillation induced by vortices (vortex-induced vibrations or VIV) that can cause premature fatigue of lead sheath in cable installed with free spans.

Comparing the 1986 and 2009 Cigre studies on cable reliability it can be observed that respect to the past technological evolution, better engineering and development of installation techniques, subsea power cables and joints fault rate has sensibly diminished.

For what concern umbilicals it’s worth of note that specially in deep and ultradeepwater installation, it’s mandatory to ensure that none of the cables, hydraulic fluids, or tubes deform to an unacceptable level under the high tension loads.

According to [46] an in-depth analysis of the stresses created during installation can ensure that the necessary criteria for successful, fatigue-minimizing installation are met and immediate or subsequent problems avoided. Dynamic analysis software tools that are capable of modeling umbilicals as a single homogeneous structure thus do not discriminating among the individual components (conservative approach) and of breaking down the global stress into axial, bending, and frictional components for each of the discrete elements of the umbilical are available. The model quantifies relative movement and deformations of all the components, armour layers, and extruded layers, with the frictional forces between them. Importantly, the model can calculate these inter-component friction forces, whatever is the complexity of the umbilical. From the models it is possible to understand how avoiding damaging and minimizing fatigue stresses that are related to installation: information that can be gained are for example how much compression the tensioner can apply and whether or not the tensioner is sufficiently sensitive in the tension it applies, impact of environmental loading (wave height, current and wind strength) on tensions, potential compression at the touchdown point.

5.3 Installation and O&M of substations

According to [47] offshore substations designs until now have seen a complete topside module, containing all the HV, MV and operational equipment installed onto a piled jacket or mono-pile foundation. Dimensions and weights of such a type of offshore substations require, for their installation, a floating heavy lift crane on an anchored barge, with transportation of foundations and topside carried out by another barge or by the same installation barge.

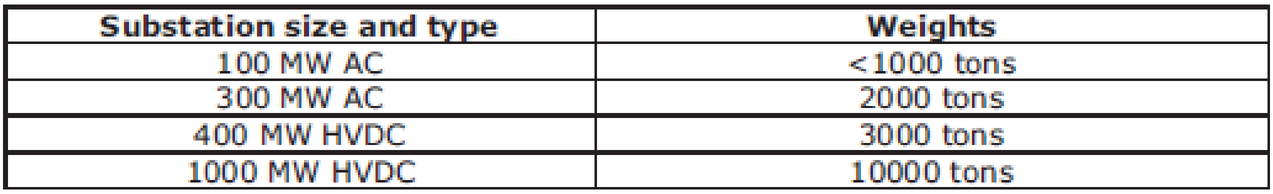
Self installing and floating design have been proposed too that avoid the use of heavy lift barges and are indicated as cost and time effective alternative solutions [48, 49].

At the moment the first floating, self-erecting substation, based on the Mobile Offshore Application Barge (MOAB), has been installed by Alstom and Keppel Verolme: it’s will be dedicated to an offshore wind farm of the German North Sea, under construction. During installation, this platform uses a suction can method to set the foundations to the sea bed, that is more respectful of the local environment compared to the traditional “pile-driving” technology.

The design is also completely self-contained to protect the electrical equipment against the harsh offshore conditions. The platform can be completely removed after its lifetime-cycle [50].

Currently operation and maintenance offshore substations is carried out from an onshore support base using small fast crafts to daily ferry technicians. For seasonal planned maintenance, requiring offshore bigger support facilities, small jack-up intervention vessels with crane capacity can be used. These considerations are applicable for sites close to shore and characterized by relatively sheltered waters; for larger sites, located far from shore, O&M requirements become more sophisticated requiring also an infield helicopter for daily transports and bigger jack-up intervention vessels for seasonal O&M activities. Offshore substations with permanent living quarters and helideck are currently under development and will be installed in German waters in the next 2-3 years [47].

Typical weight of topsides parts of substation are indicated in Table 2 (source ABB).



Substation size and type	Weights
100 MW AC	<1000 tons
300 MW AC	2000 tons
400 MW HVDC	3000 tons
1000 MW HVDC	10000 tons

Table 2 - Substation sizes and weights

Regarding their transportation and installation it can be said that not many crane vessels with lifting capacity beyond 1000 tons operate in Northern Europe and the majority of them are not suited to operate in shallow waters: platforms installed in sections can reduce crane requirements. For example gravity base structures for HVDC platforms can be transported on site by tugs, are position secured by their own weight, have a low dependence in installation from weather conditions, they are designed for remote operation and prepared for helicopter and boat access and have living quarter and equipment storage capabilities and don’t require for transformer replacement.

For subsea connection unit/substation the following general considerations can be made: equipment contained in the would need to be maintained over its lifetime and needs to be accessible in event of a failure, apart from elements declared maintenance free by the manufacturer. Maintenance of subsea substation could be extremely difficult and expensive at certain water depths and sea state conditions, thus requiring a high availability figures for these components.

5.4 5.4 Subsea equipment

Subsea equipment used during installation and maintenance activities relevant for offshore energy farm and oil and gas sector is various in relation to tasks for which it is employed, mode of operation and level of threat towards nearby subsea assets.

Among subsea equipment we will focus on Remotely operated vehicle, jetting legs, and mass flow excavators.

Remotely Operated Vehicles, or ROVs, are robots used to perform underwater activities [51]; they can be controlled from the surface by means of an umbilical connection containing communications and energy cables/links. It can be said that they reply to human divers limitation of intervention due to maximum admitted depth for submersion and the high risks associated.

A wide variety of ROVs exists, equipped with particular tools according to the specific task for which they are used: a common feature is constituted by visual device, such as a camera, to see under the water. The oil and gas sector has made extensive use of ROVs for drilling and construction of subsea structures even in very deep waters.

The first tethered ROV is of 1953 and its technology was firstly used to retrieve equipment lost at sea relevant to military activities. The oil and gas sector was the first field for commercial application.

Also the sizes of ROVs varies according to the task they have to perform: we speak about Small Electric Vehicles used primarily to observe and inspects subsea environments or objects, that carry a camera and can reach water depth of 300m.

Their evolution is constituted by High Capability Electric ROVs , able to reach water depths of up to about 6000 meters and still equipped only with video cameras. The Work Class Vehicle is electrically and hydraulically powered and, having the most a seven-function manipulator and a five-function grabber, can be used to perform some more serious work subsea, (for instance they can offer drilling and construction support) even if payload and lift capabilities are limited.

Work class ROV (WROV) usually constitute a common equipment of cable repair vessels and can be used in survey campaign, for fault detection, burial, de-burial activities they have power of hundreds of kW. Heavy Work Class Vehicle ROV are the most advanced solution, used up to about 3000m water depths. In the military field studies are ongoing for the realization of Autonomous Underwater Vehicles (AUVs) that constitute the next step in ROV technology , even if it is reasonable to think that hybrid solutions between the AUV and ROV, with less umbilicals needed to connect the subsea robot to its above-water controller, will be used as an intermediate development step.

Jetting legs or vertical injectors are rigid legs usually deployed by an anchored barge: they are used for simultaneous lay and burial of cables into sands or clays that can be fluidized. Typically the jetting leg is suspended from the barge crane and held back by guide wires during the barge progression progresses along the lay track. Burial depth can be controlled by raising or lowering the tool.

Ploughs for cable and pipeline burial can be used for post lay burial as well as simultaneous lay and burial works tools. Ploughs can be pulled by a barge using an anchor spread or by self-propelled vessel.

Mass flow excavators (MFE's) can be used for cable de-burial in water depths above 10m and can be suspended above the work area and use high volume pumps to 'blow' non-cohesive soils from the target area or operated as tracked vehicles .

5.5 Decommissioning aspects

Although there is not a unique guidance to offshore facilities decommissioning [45], it is reasonable to think that offshore structures would have to be removed to the seabed (partial removal) to preserve safety of navigation unless the removal of a particular component can be considered not viable because it can serve a new use, it constitute an unacceptable risk for personnel or environment, it's too costly or impracticable for weights and distances involved.

Cables would be disconnected once isolated offshore and pulled out of the J/I-tubes. Subsea cables can be left buried and notified as being disused or out of service if debury is considered having a strong environmental impact. Removal general is performed for beach sections of cable and sections of cable not buried (entering the energy converters).

6 Relevant standards

Currently standards expressly dedicated to submarine cables don't exist: IEC standards are used as reference although they explicitly state that they do not cover special applications like submarine ones.

Common practice is to design power cores for submarine use in accordance with IEC, add measures specific to submarine use, and include additional testing in line with CIGRE recommendations (mainly IEC 60 502, IEC 60 228,).

Other standard to reference also for installation are:

- ISO 13628-5, Petroleum and natural gas industries – Design and operation of subsea production systems – Part 5: Subsea umbilicals
- API RP 17I, Installation guidelines for subsea umbilicals
- CIGRE Electra No. 68 Recommendations for Mechanical Tests on Submarine Cables
- IEEE STD 1120, Guide for the Planning, Design, Installation and Repair of Submarine Power Cable Systems
- API 17TR7 Subsea Connector Qualification Procedures
- API 17R Flowline Connection Systems
- API 17H ROV Interfaces & ROT Intervention Systems
- API 17N Subsea Reliability & Technical Risk Management
- API 17U Insulation and Buoyancy
- API 17V Subsea Safety Systems

- CENELEC (European Committee for Electro technical Standardization) HD 629 for MV cable accessories (terminations, splices, transformers, GIS)
- EN 61442 for MV cable accessories (terminations, splices, transformers, GIS)
- IEEE 48 for MV cable terminations, splices
- IEEE 386 for transformers, GIS
- IEC 60840, IEC 60815, IEC 62067 for HV terminations
- IEC 60859, IEC 60840, IEC 62067 for HV transformers and GIS
- CENELEC HD 632, EN 61442 for HV terminations, transformers and GIS
- IEEE 48 for HV terminations
- IEEE 1300 for HV for HV transformers and GIS
- IEC 60840, IEC 62067, CENELEC HD 632, IEEE 404 for HV splices

According to the objective of this report a list of most relevant offshore standards, specification and recommended practices produced by the DNV is given [52]:

- DNV-OSS-302 Offshore Riser Systems
- DNV-OSS-306 Verification of Subsea Facilities
- DNV-OSS-304 Risk Based Verification of Offshore Structures
- DNV-OS-C101 Design of Offshore Steel Structures,
- DNV-OS-C401 Fabrication and Testing of Offshore Structures
- DNV-OS-C502 Offshore Concrete Structures
- DNV-OS-D101 Marine and Machinery Systems and Equipment
- DNV-OS-D201 Electrical Installations
- DNV-OS-F201 Dynamic Risers
- DNV-OS-H101 Marine Operations, General
- DNV-OS-H102 Marine Operations, Design and Fabrication
- DNV-OS-H203 Transit and Positioning of Offshore Units
- DNV-OS-J201 Offshore Substations for Wind Farms
- DNV RP E305 On-Bottom Stability Design of Submarine Pipelines”

- DNV-RP-F112 Design of Duplex Stainless Steel Subsea Equipment Exposed to Cathodic Protection
- DNV-RP-F201 Design of Titanium Risers
- DNV-RP-F202 Composite Risers
- DNV-RP-F203 Riser Interference
- DNV-RP-F204 Riser Fatigue
- DNV-RP-F205 Global Performance Analysis of Deepwater Floating Structures
- DNV-RP-F401 Electrical Power Cables in Subsea Applications
- DNV-RP-H102 Marine Operations during Removal of Offshore Installations
- DNV-RP-O401 Safety and Reliability of Subsea Systems

For what concern HVDC connections, presently, any proposed multi-terminal solution would be supplier specific. According to [55] this is an not felt an acceptable position as it will have serious consequences on the extendibility and choice available to utilities. The AC sector sees a huge variety components and voltages among suppliers and this has the positive effect of fostering competition and introduction of innovative approaches and techniques. For example there is no components of an AC substation (switchgear, transformer, protection equipment etc) have not necessarily to be supplied by the same manufacturer. To promote a similar level of choice in the DC sector RG NS members are participating in a CENELEC working group looking at DC Grid standards.

Worth of note are grid connection codes and interconnection guidelines and standards as they represent an essential element to cope with for energy delivery to the grid.

For conventional electric power from large hydro, thermal or nuclear energy sources numerous established norms have been produced, while for many renewable technologies special norms have been recently introduced and some of them still need further development.

In the following tables a short list of reference documents is reported based on standards and guidelines developed by utilities, commissions and organizations in wind and other generator, distributed generators and offshore engineering areas [53].

Name	**Type**	**Emphasis**
Ocean Energy		
WaveNet- Thematic Network	Guideline	Ocean Energy and Interconnection

BPAInterconnection Question	Guideline - Questionnaire	Ocean Energy and Interconnection
Powertech Labs – Accepting Criteria	Guideline	Ocean Energy and Interconnection
Carbon Trust- Guideline for Design and Operation	Guideline- Review	Ocean Energy and Broad issues
EMEC. – Marine Energy Draft Standard	Draft Standard	Grid interface of ocean energy generators
North American – Pacific Northwest Utility Perspectives		
BPATransmission Interconnection	Technical Requirement	Any Generator
BPA – Small Generator Interconnection	Standard, Agreement and Procedure	Any Generator
Federal - Small Generator Interconnection	Agreement and Procedure	Any Generator
BC Hydro Low Voltage	Interconnection Standard	Any Generator

BCTC	Standard	Any Generator
ABB	Guideline	Wind Generator
Distributed Generation (DG) and Distribution systems		
IEEE Std 1547	Standard	Distributed Generator - Interconnection
MicroPower Connect	Guideline	Distributed Generator - Interconnection
IEEE Std C62.41.2TM-2002	Standard	Distribution Network
IEE EN 50160	Standard	Distribution Network
IEEE Std 1547.1™-2005	Standard	Distributed Generator - Test Procedure
IEEE Std 1453™-2004	Standard	Test Procedure
IEEE Std. 519-1992	Standard	Test and Practice Procedure
IEEE Std C62.45TM-2002	Standard	Test Procedure
IEC 62116 Protection	Standard	Protection

Requirement		Requirement
UL 1741	Standard	Protection Requirement
IREC	Review	Any Distributed Generator
Wind Energy		
E.ON Offshore Wind	Requirements	Offshore Wind Park Integration
IEC 61400-3 Offshore Wind – Design	Standard	Offshore Wind – Design
IEC61400-1	Standard	Wind – Safety
IEC 61400-12-1	Standard	Wind – Testing
IEC 61400-21	Standard	Wind – Power quality
IEC TS 61400-25 Wind – Communication and Control	Standard	Wind – Communication and Control
Offshore Engineering		
IEC 60092	Standard	Design and Operation
IEC 61892	Standard	Design and Operation
IMO MODU Code 1989	Standard	Design
IEC publication 60092-504	Review/Draft	Operation

Table 3 – Shot list of reference documents [53].

7 Costs considerations

For large scale wind farms the electrical system (comprising collection and export phases) can represent more than 20% of the project's capital expenditure and submarine power cables cover a considerable part of this cost. A similar share is expected for wave farms.

Submarine power cables are very volatile in costs principally for variability of material costs, mobilization costs, seabed conditions strongly impacting installation, and scarce availability of equipment.

The main factors affecting the cable cost are:

- voltage rating of the cable
- cross sectional area (CSA) of the conductor
- installation costs

A cost comparison for MV/HV subsea cables is described in [54]. The principal results of the study are reported in Figure 54.

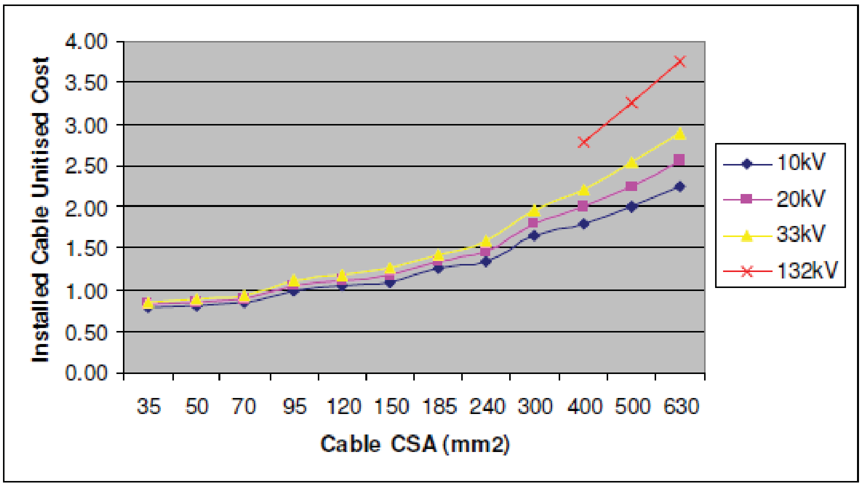


Figure 81 - Costs comparison on outputs of a unitized cost model results [54].

Cost data for HV cables can be found in [55] and are listed in the following tables.

HVDC Extruded Subsea Cable		
Cross-sectional Area (mm2)	**€/m_supplied** **150 kV**	**€/m_supplied*** **320 kV**
1200	230 – 460	345 – 518
1500	288 – 460	345 – 518
1800	345 – 518	345 – 575
2000	345 – 575	403 – 660

Table 4- HVDC Extruded Subsea Cable costs [55].

Mass Impregnated Insulated Subsea Cable		
Cross-sectional Area (mm2)	**€/m_supplied** **400 kV**	**€/m_supplied*** **500kV**
1500	403 – 660	460 – 660
1800	460 – 660	460 – 690
2000	460 – 690	460 – 748
2500	575 – 805	575 – 863

Table 5- Mass Impregnated Insulated Subsea Cable costs [55].

HVAC 3 Core Subsea Cable		
MVA Rating	**Voltage**	**Cost [€/m_supplied*]**
200	132 kV	518 – 805
300	220 kV	575 – 863
400	245 kV	748 – 1150

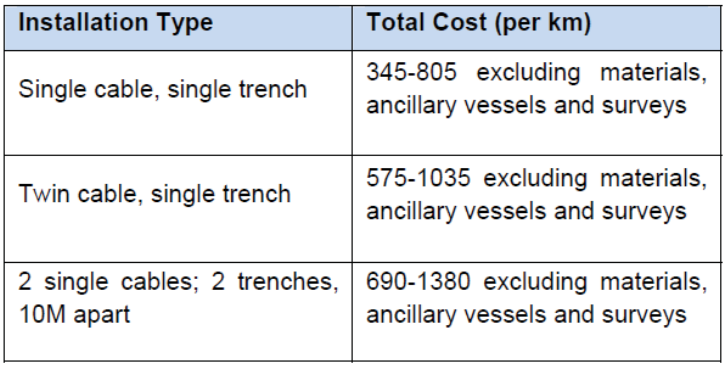
Table 6- HVAC 3 Core Subsea Cable costs [55].

Data contained in the tables reported above are based on these considerations:

- Price given is for total supplied cable cost including metal core, although commodity costs are volatile and comprise some 30%-40% of total cost
- For DC solutions the cost per route-km will depend upon the number of poles and the number of cables per pole

- Figures presented are based upon a moderate level of competitive intensity, but can vary significant depending upon how busy factories become
- Prices based upon input from manufacturers tempered with knowledge from recent known contracts

In the same document is stated that transmission subsea cables installation costs range from 230 – 977.5 €/route-metre. The cost variances are a result of what already stated above. Illustrative cost in k€ for some cable configuration are indicated in Table 6.



Installation Type	Total Cost (per km)
Single cable, single trench	345-805 excluding materials, ancillary vessels and surveys
Twin cable, single trench	575-1035 excluding materials, ancillary vessels and surveys
2 single cables; 2 trenches, 10M apart	690-1380 excluding materials, ancillary vessels and surveys

Table 7 - Illustrative costs in k€ for various cable configurations [55].

Table 7 [55] shows costs for cable connectors which are in agreement with what reported in [54]

Connectors	
Type	**Costs [k€]**
Permanent/factory cable splices/joints)	30-40
Mateable splice/joint housing	75-100
Dry-mate connectors	100-150
Wet-mate connectors	200-300

Table 8 - Expected costs for cable connectors [54].

An overview of transmission technology costs is reported in the rest of the present paragraph.

Voltage Source Converters	
Specifications	**Unit cost [M€][1]**

500 MW 300 kV	75 – 92
850 MW 320 kV	98 – 105
1250 MW 500 kV	121 – 150
2000 MW 500 kV	144 – 196
1. Pricing including AC switchyard costs and excludes platform costs.	
Current Source Converters	
Specifications	**Unit cost [M€]**[2]
1000 MW 400 kV	81 – 104
2000 MW 500 kV	150 – 184
3000 MW 600 kV	196 – 230
2.Parametrically estimated from known recent CSC contracts.	
Transformers	
Specifications	**Unit cost [M€]**[3]
90 MVA 132/11/11 kV	0.8 – 1.5
180 MVA 132/33/33 or 132/11/11 kV	1.15 – 2.07
240 MVA 132/33/33 kV	1.4 – 2.3
120 MVA 275/33 kV	1.4 – 1.84
240 MVA 275/132 kV	1.73 – 2.3
240 MVA 400/132 kV	2.07 – 2.53
3.Prices do not include civil works or associated bay works that can approximately double the total installed bay cost, but are likely to be an element of a main works contractor costs. Cost subject to fluctuation based on changes to commodity indices.	

<table>
<tr><th colspan="2">HVAC GIS Switchgear</th></tr>
<tr><th>Specifications</th><th>Total Substation Cost per Bay[M€][4]</th></tr>
<tr><td>132 kV</td><td>1.26 – 1.61</td></tr>
<tr><td>275 kV</td><td>3.34 – 3.68</td></tr>
<tr><td>400 kV</td><td>4.37 – 4.72</td></tr>
<tr><td colspan="2">4. Cost figures are for installed substation complete, including civil works.</td></tr>
<tr><th colspan="2">Shunt Reactors</th></tr>
<tr><th>Specifications</th><th>Supplied Cost[M€][5]</th></tr>
<tr><td>60 MVAr/13 kV</td><td>0.58 – 0.92</td></tr>
<tr><td>100 MVAr/275 kV</td><td>2.76 – 2.99</td></tr>
<tr><td>200 MVAr/400 kV</td><td>2.53 – 2.76</td></tr>
<tr><td colspan="2">5.Prices are based upon a unit, delivered and assembled but exclude all civil and structural works associated. Associated civil costs can approximately double the total installed bay cost but are likely to be anelement of a main works contractor costs.</td></tr>
<tr><th colspan="2">HVAC Shunt Capacitor Banks</th></tr>
<tr><th>MVAr of capacitive reactive compensation</th><th>Installed Cost[M€][6]</th></tr>
<tr><td>100</td><td>3.45 – 5.75</td></tr>
<tr><td>200</td><td>4.6 – 8.05</td></tr>
<tr><th colspan="2">Static VAR Compensators</th></tr>
<tr><th>MVAr of reactive compensation</th><th>Installed Cost[M€][6]</th></tr>
<tr><td>100</td><td>3.45 – 5.75</td></tr>
<tr><td>200</td><td>11.5 – 17.25</td></tr>
<tr><th colspan="2">STATCOMs</th></tr>
<tr><th>MVAr of reactive compensation</th><th>Installed Cost[M€][6]</th></tr>
<tr><td>50</td><td>3.45 – 5.75</td></tr>
</table>

100	5.75 – 11.5
200	11.5 – 23
6. Costs are for a total installed cost, including associated site works.	
HVAC Overhead Lines for connection to AC land systems	
Description	**Total Cost[M€][7]**
Cost per route km 400 kV, double circuit	1.73 – 2.19
Cost per route km 132 kV, double circuit	0.81 – 1.04
Cost per route km 132 kV, single circuit	0.58 – 0.69
7. Prices include all installation works.	

Table 9- Costs for transmission technology elements [55].

For what regards connection to AC land systems, it is important to note that, in particular areas, HVAC partial undergrounding may complement the overhead lines. According to [56], the investment cost for underground cable solutions can be considered typically 5 to 10 times higher than overhead line costs for the section in which partial undergrounding is applied.

In [55] also costs of offshore substations are given considering some case studies. They are summarized in Table 9.

AC Platforms costs [M€]			
Case Study 1: 132/33 kV 300 MW HVAC (25 x 20 x 18 m, weighing 2000 tonnes)			
	Water depth 20-30m	**Water depth 30-40m**	**Water depth 40-60m**
Topside	21 – 26	21 – 26	21 – 26
Jacket	5.75 – 9. 2	6.9 – 11.5	9.2 – 13.8

<table>
<tr><td>Install</td><td>5.75 – 9.2</td><td>6.9 – 9.2</td><td>6.9 – 11.5</td></tr>
<tr><td>Self Installing</td><td>33 – 38</td><td>35 – 39</td><td>36 – 40</td></tr>
<tr><td colspan="4">Case Study 2: 220/33 kV 500 MW HVAC
(40 x 30 x 18 m, weighing 2500 tonnes)</td></tr>
<tr><td></td><td>Water depth
20-30m</td><td>Water depth
30-40m</td><td>Water depth
40-60m</td></tr>
<tr><td>Topside</td><td>-</td><td>27.5 – 32</td><td>27.5 – 32</td></tr>
<tr><td>Jacket</td><td>-</td><td>9.2 – 11.5</td><td>11.5 - 15</td></tr>
<tr><td>Install</td><td>-</td><td>5.75 – 9.2</td><td>6.9 – 11.5</td></tr>
<tr><td>Self Installing</td><td></td><td>42.5 – 46</td><td>43.7 – 49.5</td></tr>
<tr><td colspan="4"></td></tr>
<tr><td colspan="4">DC Platforms costs [M€]</td></tr>
<tr><td colspan="4">Case Study 1: 400 MW Voltage Source ±300 kV; Platform (3500 tonnes)</td></tr>
<tr><td colspan="2"></td><td colspan="2">Water depth
30-50m</td></tr>
<tr><td colspan="2">Topside</td><td colspan="2">32 – 38</td></tr>
<tr><td colspan="2">Jacket</td><td colspan="2">9.2 – 12.65</td></tr>
<tr><td colspan="2">Install</td><td colspan="2">18.4 – 23</td></tr>
<tr><td colspan="2">Self Installing</td><td colspan="2">69 – 80.5</td></tr>
<tr><td colspan="4">Case Study 2: 800 MW Voltage Source ±300 kV or 1000 MW Voltage Source ±500 kV; Platform (8000 tonnes)*</td></tr>
<tr><td colspan="2">Topside</td><td colspan="2">69 – 92</td></tr>
<tr><td colspan="2">Jacket</td><td colspan="2">23 – 29</td></tr>
<tr><td colspan="2">Install</td><td colspan="2">31 – 36</td></tr>
<tr><td colspan="2">Self Installing</td><td colspan="2">138 – 167</td></tr>
<tr><td colspan="4">*Figures based on traditional designs, not self-installing topsides.</td></tr>
</table>

Table 10- Offshore Platforms costs [55].

In [57] a wave energy farm grid connection costing case study, in the Irish context, is performed. This case study assumes a 20MW wave farm connected to the Irish distribution 38kV grid and it is considered a representative study for early commercial wave farm development. Reference location is the wave energy test site off Belmullet. The layout assumes each 1 MVA WEC spaced approximately 500m apart in an array of 4 deep and 5 across, for a total area occupied of approximately 9km^2. The WECs are connected together in groups of 5, with each group being connected to a central floating substation. As for WTGs each WEC is assumed to contain an LV/MV transformer and associated switchgear: cables between WECs and the floating substation is then considered to be dynamic (flexible) MV cable, not to be buried. A floating substation, hosting offshore electrical equipment consisting of two 10MVA MV/38kV step-up transformers, is proposed since it is thought to be less expensive effective than a fixed structure at 60-90m water depths. The export cable is a 38kV static cable, buried where the seabed permits and with rock protection over 1km.

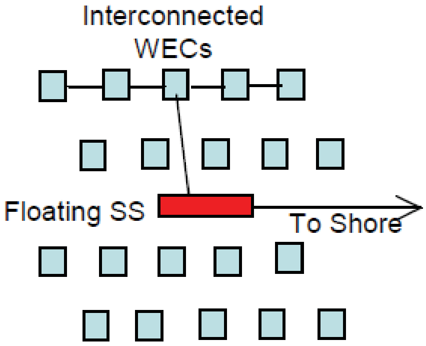
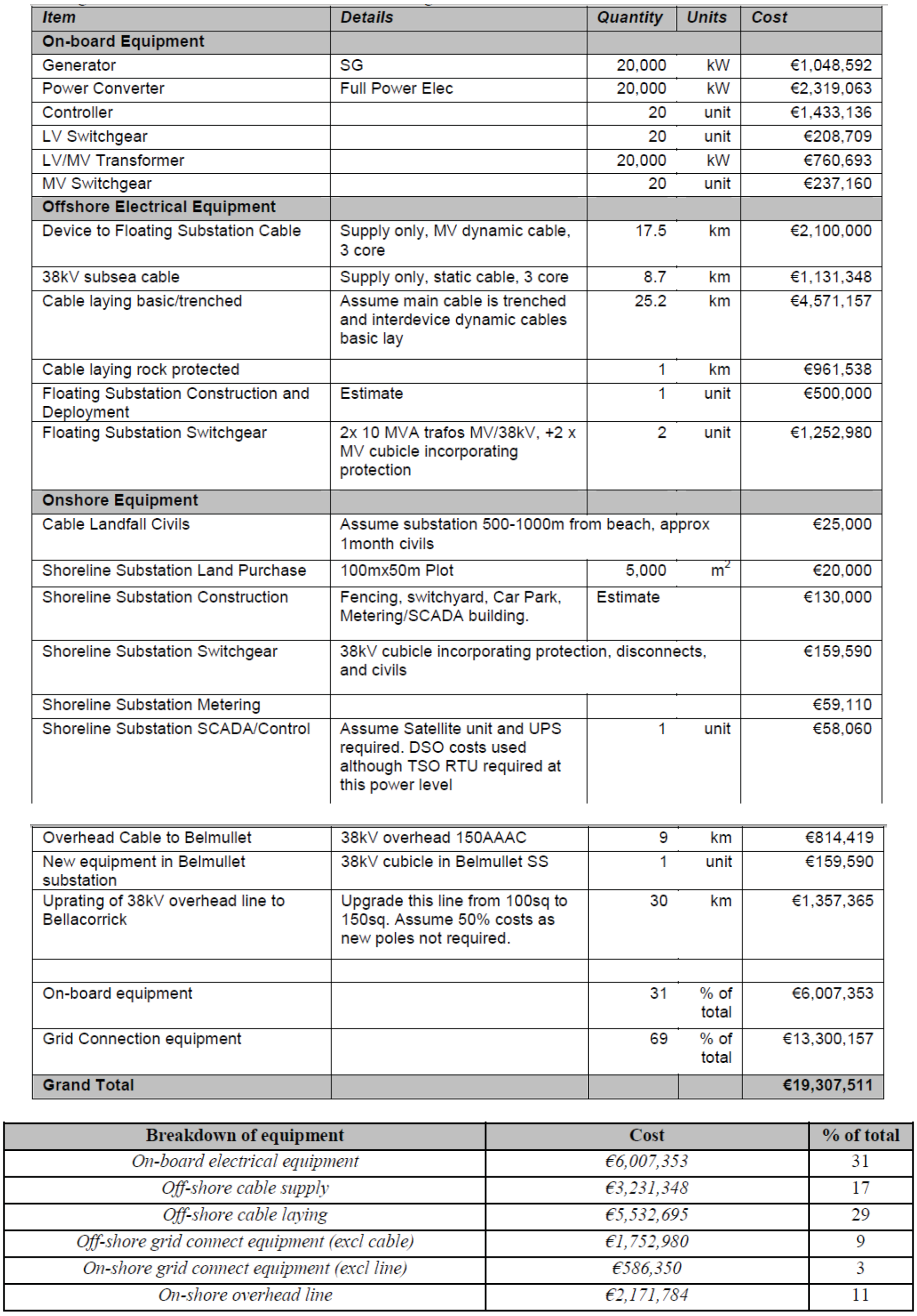


Figure 82 - Layout of wave farm considered in the case study [57].

Principal results, obtained are highlighted in Figure 83.



Item	Details	Quantity	Units	Cost
On-board Equipment				
Generator	SG	20,000	kW	€1,048,592
Power Converter	Full Power Elec	20,000	kW	€2,319,063
Controller		20	unit	€1,433,136
LV Switchgear		20	unit	€208,709
LV/MV Transformer		20,000	kW	€760,693
MV Switchgear		20	unit	€237,160
Offshore Electrical Equipment				
Device to Floating Substation Cable	Supply only, MV dynamic cable, 3 core	17.5	km	€2,100,000
38kV subsea cable	Supply only, static cable, 3 core	8.7	km	€1,131,348
Cable laying basic/trenched	Assume main cable is trenched and interdevice dynamic cables basic lay	25.2	km	€4,571,157
Cable laying rock protected		1	km	€961,538
Floating Substation Construction and Deployment	Estimate	1	unit	€500,000
Floating Substation Switchgear	2x 10 MVA trafos MV/38kV, +2 x MV cubicle incorporating protection	2	unit	€1,252,980
Onshore Equipment				
Cable Landfall Civils	Assume substation 500-1000m from beach, approx 1month civils			€25,000
Shoreline Substation Land Purchase	100mx50m Plot	5,000	m^2	€20,000
Shoreline Substation Construction	Fencing, switchyard, Car Park, Metering/SCADA building.	Estimate		€130,000
Shoreline Substation Switchgear	38kV cubicle incorporating protection, disconnects, and civils			€159,590
Shoreline Substation Metering				€59,110
Shoreline Substation SCADA/Control	Assume Satellite unit and UPS required. DSO costs used although TSO RTU required at this power level	1	unit	€58,060
Overhead Cable to Belmullet	38kV overhead 150AAAC	9	km	€814,419
New equipment in Belmullet substation	38kV cubicle in Belmullet SS	1	unit	€159,590
Uprating of 38kV overhead line to Bellacorrick	Upgrade this line from 100sq to 150sq. Assume 50% costs as new poles not required.	30	km	€1,357,365
On-board equipment		31	% of total	€6,007,353
Grid Connection equipment		69	% of total	€13,300,157
Grand Total				**€19,307,511**

Breakdown of equipment	Cost	% of total
On-board electrical equipment	*€6,007,353*	31
Off-shore cable supply	*€3,231,348*	17
Off-shore cable laying	*€5,532,695*	29
Off-shore grid connect equipment (excl cable)	*€1,752,980*	9
On-shore grid connect equipment (excl line)	*€586,350*	3
On-shore overhead line	*€2,171,784*	11

Figure 83 - Costs results for the case study considered [57].

8 RELEVANT OFFSHORE PROJECTS

In this chapter a list a list of some offshore projects, divided in AC and DC connection to GRID alternative, is reported.

AC offshore projects:

- Gudrun Oil and Gas Field, Norway: 55 km, 20 MW, 52 kV power cable from the Sleipner oil field, Cu conductors and integrated optical fiber cable.
- Thornton Bank Offshore Wind Farm Phase 2 & 3, Belgium:38 km, 150 MW, 150 kV shore connection power cable with Al conductors and integrated optical fiber cable and 26 + 34 km 33 kV inter-turbine cables with Al and Cu conductors and integrated optical fiber cable.
- Nordsee Ost Offshore Wind Farm, Germany: 63 km, 33 kV inter-turbine cables with Al conductor and integrated optical fiber cable.
- Goliat Floating Oil Platform, Norway: 104,5 km, 75 MW, 123 kV static submarine cable with Cu conductors and 1,5 km, 75 MW, 123 kV dynamic submarine cable with Cu conductors and integrated optical fiber cable.
- Gjoa Offshore Oil Platform, Norway: 98 km, 40 MW, 115 kV shore connection power cable, including 1,5 km dynamic power cable, to floating platform. Cu conductors integrated optical fiber cable.
- Thornton Bank Offshore Wind Farm, Belgium: 38 km, 150 MW, 150 kV shore connection power cable with Al conductors and integrated optical fiber cable and 4 km 33 kV inter-turbine cables with Al conductors and integrated optical fiber cable.
- Prinses Amaliawindpark (Q7), the Netherlands: 28 km, 120 MW, 170 kV shore connection power cable with Cu conductors and integrated optical fiber cables and 40 km, 24 kV inter-turbine cables with Al and Cu conductors and integrated optical fiber cable.
- Lillgrund Offshore Wind Farm, Sweden: 33 km, 110 MW, 145 kV shore connection power cable and 36 kV inter-array cables with Cu conductors and integrated optical fibers.
- Burbo Banks Offshore Wind Farm, UK: 40 km, 90 MW, 36 kV inter-turbine and shore connection power cables with Cu conductors.
- Abu Safah Oil Field, Saudi Arabia: 50 km, 52 MVA, 115 kV shore connection power cable with Cu conductors.
- Yttre Stengrund Offshore Wind Farm, Sweden: 22 km, 10 MW, 24 kV interturbine and shore connection power cables with Al conductors and integrated optical fibers.
- Utgrunden Offshore Wind Farm, Sweden: 11 km, 10 MW, 24 kV inter-turbine and shore connection power cables with Al conductors and integrated optical fiber cable.

- Samso Offshore Wind Farm, Denmark: 7.5 km, 20 MW, 36 kV inter-turbine and shore connection power cable with Cu conductors integrated optical fiber cable.
- Nysted Offshore Wind Farm, Denmark: 55 km, 165 MW, 36 kV inter-turbine power cables with Al- and Cu conductors and integrated optical fiber cable.

DC offshore projects:

- DolWin2 Offshore Wind Project, Germany: 2x45km, 900 MW, +/- 320 kV HVDC Light® submarine power cables with Cu conductor and 2x90 km, 900 MW, +/- 320 kV HVDC Light® underground cables with Al conductor. 2x12 km, 200 MW, 155 kV AC submarine cable with Cu conductors and integrated optical fiber cable.
- DolWin1 Offshore Wind Project, Germany: 2x74 km, 800 MW, +/- 320 kV HVDC Light® submarine power cables with Cu conductor and 2x90 km, 800 MW, +/- 320 kV HVDC Light® underground cables with Al conductor. 7,5 km, 200 MW, 155 kV AC submarine cable with Cu conductors and integrated optical fiber cable.
- BorWin1 Offshore Wind Project, Germany: 2x125 km, 400 MW, +/-150 kV HVDC Light® submarine power cables with Cu conductor and 2x75 km, 400 MW +/-150 kV HVDC Light® underground cables with Al conductor.
- Troll A Offshore Gas Field Platform, Norway: 4x68 km, 2x40 MW, +/-80 kVHVDC Light® submarine power cables c with Cu conductors.

9 Conclusions and recommendations

The state of the art of the connection techniques between offshore energy farm and land main grid can be resumed as follow:

- Low power farms (<30MW) closed to shore (<20km)
  Type: Alternating current AC 50/60 Hz
  Voltage level: Medium Voltage MV (max 33kV)
  Underground cable: 3-core XLPE
  Subsea cable: 3-core XLPE
  Offshore platform: NO
  System: FACTS are required onshore for reactive power compensation

- Farms near to shore (<100km)
  Type: Alternating current AC 50/60 Hz
  Voltage level: High Voltage HV (max 275kV, typical 150kV)
  Underground cable: 3x1-core or 3-core XLPE
  Subsea cable: 3x1core or 3-core XLPE
  Offshore platform: YES
  System: FACTSs are required onshore and offshore for reactive power compensation

- Farms far to shore (>100km)
  Type: Direct current DC - Bipole configuration
  Voltage level: High Voltage HV (typical +/-320kV)
  Underground cable: 2x1-core Mass Impregnated MI or DC XLPE (if V<=320kV)

Subsea cable: 2x1-core Mass Impregnated MI or DC XLPE (if V<=320kV)
Offshore platform: YES
System: Voltage Source Converter VSC + Filtering System (FACTS are not required)

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