WP 3: Technologies state of the art

Task 3: Grid integration aspects

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1 Introduction

1.1 Objectives

Within WP 3 of the EU ORRECCA project the state of the art of current offshore Renewable Energy converters and platform technologies will be analyzed as they are being used in the three sectors:

1. the oil and gas industry,
2. in offshore wind and
3. in ocean energy.

The analysis will cover structural requirements and designs of the different technical solutions and describe realized systems, including demonstration and pilot projects. Lessons learned from these projects will be provided**.**

1.2 WP3 - Task 3: Grid integration aspects

A technical aspect to be described and analysed is the **grid connection and grid integration** of offshore RE farms. This includes the use of flexible cables and subsea switchgears as they are planned to be used in very first pilot ocean energy installations. Recent grid integration studies for offshore wind energy, realized in a number of European countries such as Ireland, UK, Denmark, Netherlands, Germany will be reviewed and conclusions will be developed for the roadmap under WP5. Grid integration strategies in progress in the US and Canada will integrated.

Scope

Both offshore wind energy and ocean energy sources are being involved in this ‘State of the Art’ analyses. Important to mention is the present difference in stage of development of these RE sources.

- Offshore wind energy is realized at present in (far) offshore wind farms in which typically 5 MW wind turbines are clustered to build a 400 MW wind farm; while
- Ocean energy generation systems, like wave, current, tidal energy systems are still in the prototype phase, having a production unit rated power in the order of 0.1 MW.

The electrical infrastructure of offshore wind energy and other ocean energy systems will differ much in this stage of development, but will converge as ocean energy production units and farms reach the same power levels. Cross-fertilization will help both developments.

1.3 Developments

Offshore energy generation is increasing enormously. Especially wind energy is expanding rapidly. Plans exist for more than 60 GW offshore wind power in the North Sea alone. The distances of wind farms to shore are relatively short still, but the first steps to far offshore (>50 km) are taken. With this development, dedicated technology for transporting large amounts of electric power over long distances to shore is needed. Furthermore, a good cooperation and consultation between different nations and grid companies is necessary to built for instance a future electrical European North Sea infrastructure to facilitate the ocean energy development. On 3 December 2010 ten European countries signed an agreement to jointly develop a smart electrical grid in the North Sea.

1.4 Overview

This section starts with an overview of currently used electrical systems in wind turbines and currently used offshore grid concepts. The emphasis will be on the technical aspects of these systems and some refference will be made with regard to losses, reliability, dynamic behavior and costs. The overview of the electrical systems for offshore wind energy is completed by a description of the grid requirements for these systems.

Current offshore wind turbine installation is stationary, floating wind turbines are still in an experimental stage. Ocean energy devices however, are often of the floating type, and this will result in different requirements for the first section of the power cable connected to the device. The next part of this section of the report therefore deals with subsea risers and cables.

The next two parts describe electrical systems for ocean energy and offshore oil and gas platforms. Finally, conclusions will be drawn from the presented information and ideas will be formulated with regard to mutual development benefits of the three fields of offshore power electrical systems.

2 State of the art electrical systems in wind energy application

2.1 Overview of wind turbine generator concepts

According to Steibler [2], systems for feeding electricity into a 50 Hz or 60 Hz network are coupled to a medium voltage or high voltage connecting point. Under normal conditions the frequency may be considered constant, and voltage variations are within specified values, e.g. ± 6%. Figure 2.1 shows circuits of typical system concepts of generating electric power and applied in wind turbines [2]. Using an induction generator (IG):

- (a) the electrical machine can be directly coupled forming a system of almost constant rotational speed (slip frequency below a few percent of rated frequency).
- (b) variable speed systems use a converter of the full rated power of the generator to decouple generator speed from grid frequency, or
- (c) with a converter of reduced power only for slip energy recovery. The latter requires a wound-rotor, slip-ring induction machine.

Systems with a synchronous generator(SG) practically always work fully fed with a converter since there is practically no speed variation at constant grid frequency (only the angle of the magnetic field of the rotor varies with respect to the angle of the magnetic field of the stator):

- (d) the machine may be electrically excited via slip-rings or brushless or
- (e) by permanent magnets

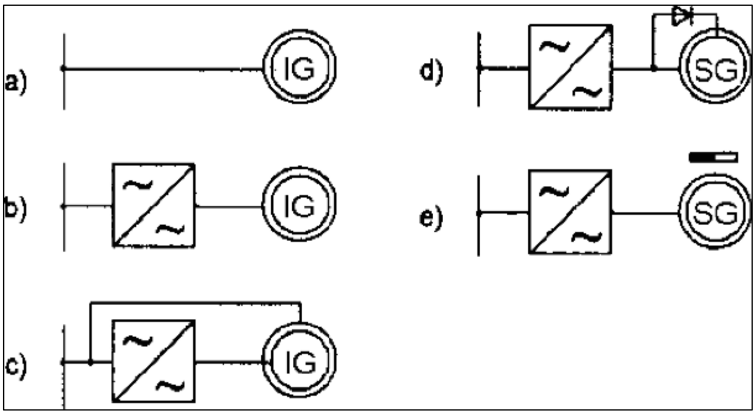


Figure 2.1 Typical concepts for generating electrical power – using induction generator [2];

1. direct coupling,
2. fully-fed,
3. doubly fed, – using synchronous generator, fully fed;
4. electrical excitation,
5. PM excitation

Modern application of these concepts in wind turbines are shown in **Figure 2.2** Part (a) depicts a conventional system, with an induction generator (G) directly connected, driven by the wind turbine via a gear box, where speed ratios of around 100 are common for ratings of 1.500 kW to over 5 MW. To avoid high rush-in currents after switching, it is usual to have a soft-starting device, consisting of a set of anti-parallel thyristors. An option is to have a dual speed system, using a generator with two sets of 3 phase windings of different pole pair number. Thus it can operated at below rated speed at below rated power, increasing the efficiency.

Figure 2.2 part (b) is typical for systems with a synchronous generator, preferably directly driven (without gear box) which implies a generator (G) with a large number of pole pairs. Generator with many pole pairs are very heavy and voluminous. Variants are known where a gear box of only moderate speed ratio of around 10 is used (Multibrid), allowing a smaller generator size. The power is fed to the grid via a converter with intermediate DC circuit which must be designed for full load (fully fed).

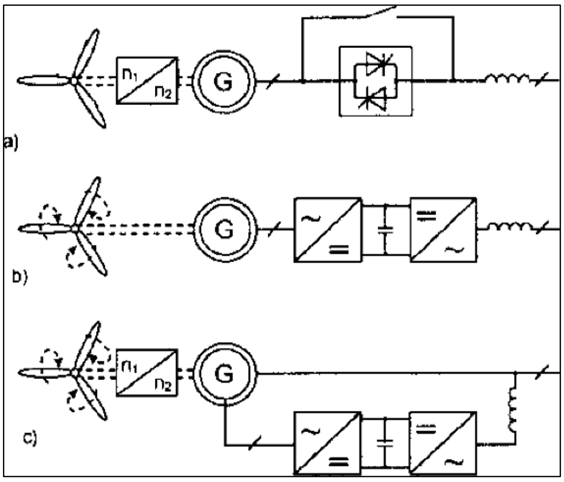


Figure 2.2 Common concepts of systems feeding into the grid [2]

Figure 2.2 part (c) is the circuit common for a system with doubly fed (slip-ring) induction generator. The term doubly-fed induction machine applies to a system where both stator and rotor winding of a slip-ring machine are connected to the grid [2]. In contrast to part figure (b) the converter rating is typically only 35% of full load to allow for a speed range of 1:2.

The doubly fed asynchronous generator system has been mentioned by Steible in [2] as a standard solution of today in modern wind energy systems, also for offshore application. To harness the wind power efficiently the most reliable system in the present era is grid connected doubly fed induction generator. The DFIG brings the advantage that the converter does not need to be rated for the machine's full rated power, while maintaining an acceptable speed range. Use can be made of a cyclo-converter or a converter with intermediate DC circuit as shown in Figure 2.3 Both rotor-side and grid-side converter (MSI, GSI) are self-commutated devices, allowing active power transfer in both directions and the adjustment of reactive power on both sides. In that case, the switching element used is the IGBT (Insulated Gate Bipolar Transistor). Note that Figure 2.3 contains a filter (F) and a transformer (T) to adapt the rotor side voltage to the grid. In most cases a crowbar is additionally provided at the rotor-side, by which in case of grid faults the rotor is switched to an external resistor to protect the machine-side converter from excess current while keeping the system connected to the grid during the fault. Staying connected during a grid fault is one of the requirements for modern large scale wind power.

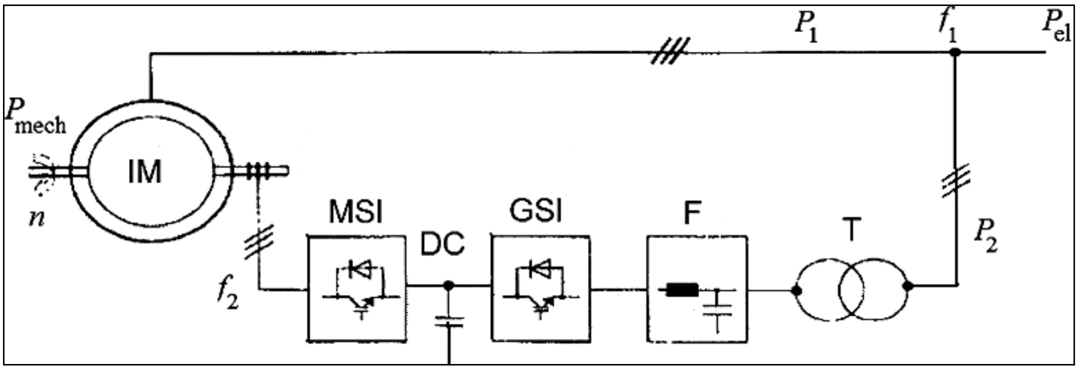


Figure 2.3 Doubly-fed induction generator with rotor-side converter

2.2 Unconventional machine types

1. Direct driven generators

In direct driven wind energy system (no gearbox) multi pole generators are applied to generate a voltage with an acceptable frequency. The rotational frequency of large wind turbines is relatively low, typically below 60 rpm, which would result in a low electric frequency for a direct drive generator with low number of pole pairs. Due to manufacturing considerations, only synchronous machines (permanent magnet or electrically excited) have found practical application in systems for direct drive while induction generators are confined to systems with gear boxes.

2. Unconventional Designs [2]
    - Axial Field Machines
    - Transversal Flux Machines
    - Variable Reluctant Machines

These types have received some scientific attention but have not been applied in commercial wind turbine concepts yet.

2.3 Generator Comparison

From the performance of the machine types discussed in the previous chapter the following conclusions can be drawn [2]:

- The asynchronous machine, especially in the form of the squirrel cage induction machine (no rotor windings, no brushes), is a robust and low cost generator. In the conventional solution directly coupled to the mains, the required reactive power is drawn from the grid. This constant speed technology may be improved by providing a second speed in the pole changing concept, preferably in the ratio 3:2.
- When using the wound rotor asynchronous machine the slip power can be recovered. The modern solution is the so-called doubly-fed asynchronous machine which allows, by means of a converter, to extract or feed power into or out of the rotor circuit. Operation with variable speeds in a ratio of typically 2:1 requires a converter designed for approximately 1/3 of the rated power.
- In the synchronous machine the required magnet flux is provided by permanent magnets or by excitation current fed into a field winding. In the latter case reactive power and terminal voltage, respectively, are adjustable.

  For variable speed solutions it is necessary to use a converter designed for the complete rated power to decouple the frequencies.

  Synchronous machines may be designed with large number of poles, to operate directly driven in wind systems without gear boxes. Pole pitch values can further be reduced by applying special concepts.

2.4 Power Electronic Converter Technology

In variable speed wind turbines, a power electronic convertor system is applied between generator and grid. This makes the (variable) electrical frequency at the generator side independent from the (fixed) grid frequency. To have a constant unidirectional torque in a generator, the rotational speeds of the stator and the rotor field have to be the same. In a variable speed generator, this is realised by either a power electronic converter connected to the stator (variable stator electric frequency) or connected to the rotor (variable rotor electric frequency)

Depending direction of the power flow and the control options, the following kinds of inverter are distinguished:

- *AC./DC converters (rectifiers)*

The power flow is from AC to DC. They transform AC current of a given voltage, frequency and number of phases into DC current. Uncontrolled devices contain diodes, normally in bridge arrangement. If the thyristor is used as switching component, the moment of conduction can be controlled but not the moment of extinction. The extinction of the switch is determined by the reversal of the voltage over the switch, which is caused by the AC voltage. Therefore this type of converter is called grid commutated. Examples are the two-pulse bridge for single-phase input, and the six-pulse bridge for three-phase input. The third type of switching device is the IGBT (Insulated Gate Bipolar Transistor). Its basic property is that it not only can be switched on by a control signal but it can also be switched off. This is called a self-commutated device. Since the switching frequency of the grid commutated device is determined by the grid frequency and the switching frequency of the self commutated device is not, the self commutated converter can be operated at a higher switching frequency. This has positive (less harmonic distortion, reactive power control) as well as negative consequences (higher losses).

- *DC/AC converters (inverters)*

The power flow is from DC to AC. They transform DC current into AC current of a certain voltage, frequency and number of phases. These devices are either grid or self-commutated. There is no principle difference between inverters and rectifiers. A converter can be operated in both ways, depending on the controller, except in case of diode switches.

- *Current-source converter (CSC) and Voltage Source Converter (VSC)*

Coupling the AC/DC and DC/AC converter by an intermediate DC circuit results in an overall AC/AC conversion. It can either be operated with impressed voltage (voltage source-converter, VSC), or with impressed current (current-source converter, CSI). In general, the thyristor based systems are of the current source type while the IGBT based systems have a voltage source characteristic.

- *DC/DC converters (choppers)*

They transform DC current of a given voltage and polarity to DC current of another voltage and polarity. Converters using an energy storage element and a

pulse-control scheme are usually called choppers.

Depending on the ratio of output-/input-voltage, we have step-up (boost) converters for ratios > 1 and step-down (buck) converters for ratios < 1. Specific converter circuits are capable of both ways of operation (buck-boost).

3 Current Offshore Grid Concepts

In this section an overview is given about today's energy transmission systems concepts to transport the offshore generated energy to the grid onshore. Offshore power transmissions makes use of cables and not overhead lines, found in most power transmission systems on land. Offshore overhead lines would require sea bottom based structures to support the air suspended non-isolated line. This would make the system expensive. Secondly, overhead lines at sea would be a major problem for sea traffic. A large enough clearance between a passing ship and the non-isolated line has to be guaranteed. Secondly, the bottom based structures would represent major obstacles, especially if weather and visibility are bad.

Important aspects of offshore electrical transmission cable systems are the system type (AC or DC), the cable type (i.e. XLPE or paper impregnated), the power rating and voltage, the reactive power consumption and the electrical losses and last but not least the price.

3.1 HVAC transmission

Several offshore wind turbine farms have been realised during the past decade. Most of these wind power systems are relatively close (<50 km) to shore and have an **HVAC** connection to the onshore grid.

An HVAC system Figure 3.1 contains the following main components, see Alegria [1]:

- AC collecting system at the offshore platform.
- Offshore substation with transformers and reactive power compensation.
- Three-phase submarine cable (generally XLPE three-core cable but multiple single core cables is also an option).
- Onshore substation with transformers and reactive power compensation.

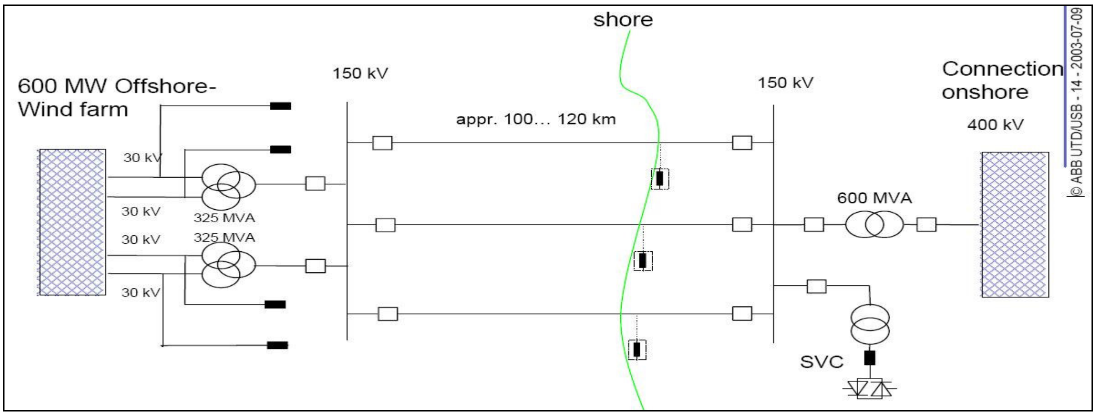


Figure 3.1 HVAC transmission system [12]

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 and 380kV AC up to about 40km. The highest voltage level for a three-core XLPE submarine cable in existence is 170 kV in the 21 km long 630 mm2 cable linking the Horns Rev Offshore Wind Farm to the Danish mainland. This level could potentially go up as high as 245 kV by employing a slightly larger insulation thickness. At present, this represents the maximum realistic voltage limit because beyond this level the three-core cable size would be so great that the production, handling and transportation would be impractical.

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, see

. 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.

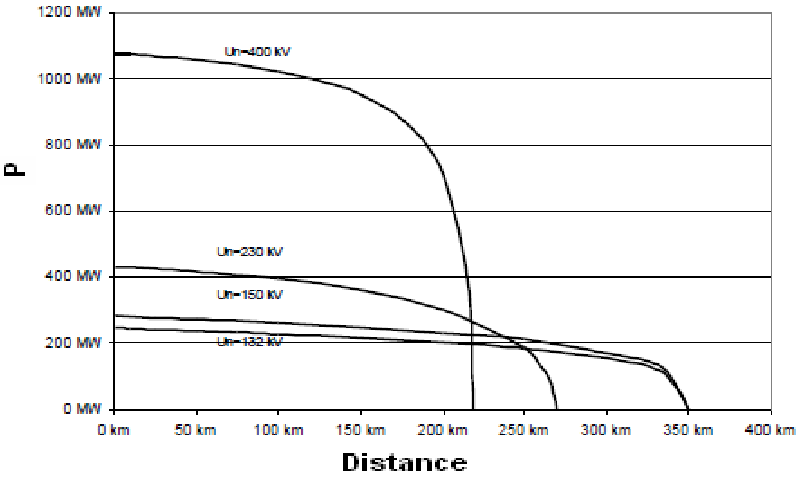


Figure 3.2 HVAC power transfer capacity as a function of transmission distance and voltage (reactive current compen-sation at both sides) [9]

As an example, in Figure 3.2, it can be seen that for distances of 100 km, there are possibilities for transmission of up to 400 MW at 230 kV and more than 200 MW at 132 and 150 kV. The latest technology on 400 kV offers the advantage of being able to carry up to 1000 MW, on distances not more than 100 km. The capability of transmission over long distances is decreased by increasing the rating of the voltage. Moreover, for the same transmission distances the electrical losses are increasing by decreasing the voltage level. For a 100 km transmission, losses of 3-4% are obtained for 400 kV and 230 kV. At first instance this seems odd, since higher voltage would suggest relative losses lower losses. However two aspects can offset this relation: the higher reactive current and the skin effect resulting in increased relative resistance at increasing cable diameters.

If there is need to connect larger amount of power at long distance, multiple connections have to be designed. The wind farm is divided into clusters with individual offshore substations and connections to the main grid. This leads to the need of more cables and construction of more than one offshore platform.

Some examples of offshore HVAC installations [1, 16].

Project	**Power (MW)**	**Transmission system (km)**	**Voltage (kV)**
Abu Safah Oil Field (Saudi Arabia)	52	50	115
Horns Rev Wind Farm (Denmark)	160	21	170
Samsö Wind Farm (Denmark)	20	7.6	36
Nysted Wind Farm (Denmark)	165	55	132
Amalia Wind Farm (The Netherlands)	120	28	170
Lillegrund Wind Farm (Sweden)	110	33	145
Burbo Banks (UK)	90	40	36
Utgrunden Wind Farm (Sweden)	10	11	24
Alpha Ventus demo wind farm	60	66	110
Sheringham Shoal UK	317	22	132

3.2 HVDC transmission

Transporting electric power offshore over longer distances is carried out as HVDC (High Voltage Direct Current). In 1954 the first HVDC transmission (20MW-100kV) was introduced between Sweden and Gotland. Conventional HVDC transmission has been widely used for many years already for delivering electrical power over long distances and/or interconnecting between two unsynchronised AC networks. Well-known international offshore DC connections have been realized between i.e. Norway – Denmark, Sweden – Poland, England – France. The greatest offshore distance bridged by DC is the recently built connection between the Netherlands and Norway: 580 km, 700 MW at 450 kV.

An elementary DC transmission system consists of a rectifier at one end of the transmission line to convert AC to DC while an inverter at the other end of the line reconverts the DC into AC. It is in principle the same system as described in the overview of wind turbine electrical systems, only on a larger scale. Offshore compatible HVDC (power electronic converters suitable for placement at an offshore platform) is still under development and currently costs considerably more than AC transmission at moderate distances. With the increase in power and voltage of the power electronic converters, however, HVDC is becoming more feasible.

As described in the overview of wind turbine electrical systems, two types of HVDC systems are available, conventional thyristor-based current-source line commutated converters (CS LCC), and the newer voltage-source self commutated converters (VS SCC) systems.

3.3 CS LCC HVDC

A CS 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 (line) 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 and an auxiliary start-up system would be necessary if it would be used to connect an offshore renewable energy farm. Figure 3.3 shows an schematic of a 12-pulse HVDC LCC transmission line. HVDC systems allow for instantaneous power control and there is no limit in the transmission distance unlike HVAC, since the distance is not limited by reactive power consumption of the cable.

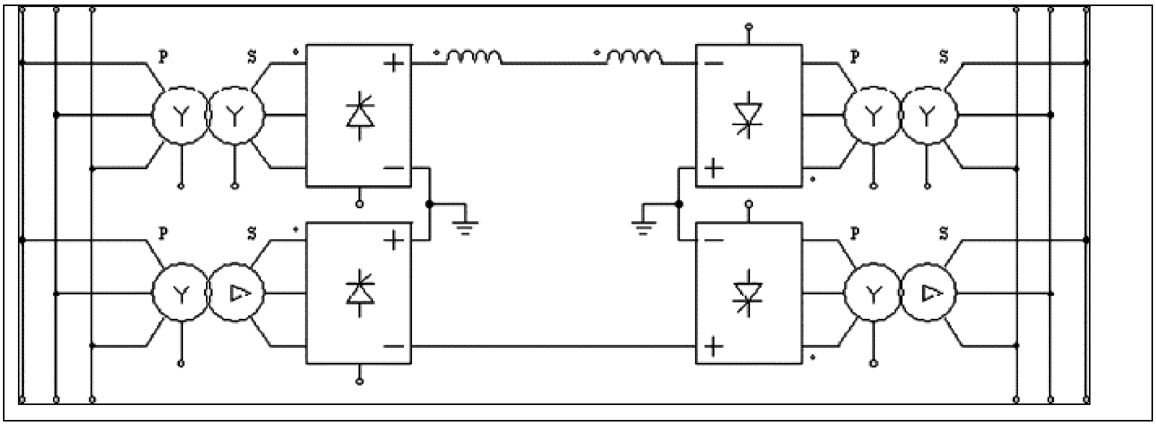


Figure 3.3 HVDC LCC conventional transmission system [1].

HVDC LCC systems have the following main components at each end of the transmission line:

- Transformers.
- LCC converters based on thyristors.
- AC and DC filters.
- DC current inductors.
- Capacitors or STATCOM for power compensation of the reactive required by the LCC converters.
- DC cable.

Some examples of offshore HVDC LCC installations [1].

Project	**Power (MW)**	**Transmission system (km)**	**Voltage (kV)**
Basslink (Australia–Tasmania)	500	290	400
Italy–Greece HVDC link	500	163	400

3.4 SC VSC HVDC

Advances in improving the performance of self-commutated semiconductor devices have led to SC VSC HVDC, commercially available as HVDC-Light (ABB) and HVDC-Plus (Siemens). The VSC converters often use insulated gate bipolar transistor (IGBT's) and allow independent control of both active and reactive current.

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.

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).

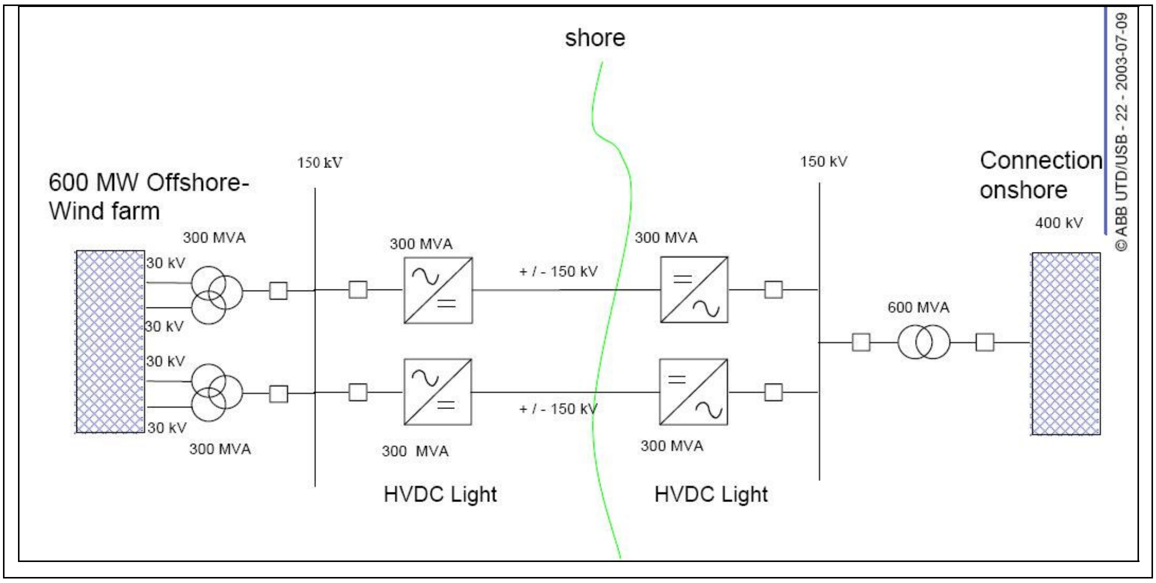


Figure 3.4 HVDC VSC transmission system [12].

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 Hellsjön 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.

Figure 3.4 shows the schematic of a HVDC VSC transmission system.

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.

An HVDC VSC system has the following main components:

- Transformers.
- VSC HVDC converters (one offshore and one onshore).
- AC and DC filters.
- DC current capacitors.
- DC cable.

A DC transmission system can consist of one cable (monopolar with earth return) or two cables (bipolar or monopolar with zero voltage return).

Some examples of offshore HVDC VSC installations [1]

Project	**Power (MW)**	**Transmission system (km)**	**Voltage (kV)**
Cross Sound (U.S.A.)	330	40	150
Gotland Light (Sweden)	50	98	80
Tjaereborg Light (Denmark)	7.2	4.3	9
Troll A Gas Platform (Norway)	80	68	80
BARD offshore 1: Borwin 1	400	125 offshore and 75 onshore	400

3.5 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 and shield resistance). Figure 3.5 gives an example of the losses in four different AC and DC systems of 1 GW at distances of 100, 200 and 500 km [18]. The different colours represent the different electrical components. 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 [10] HVDC system losses are mentioned:

- VSC HVDC: typical 4 - 6 %
- LCC HVDC: typical 2.5 – 4.5 %.

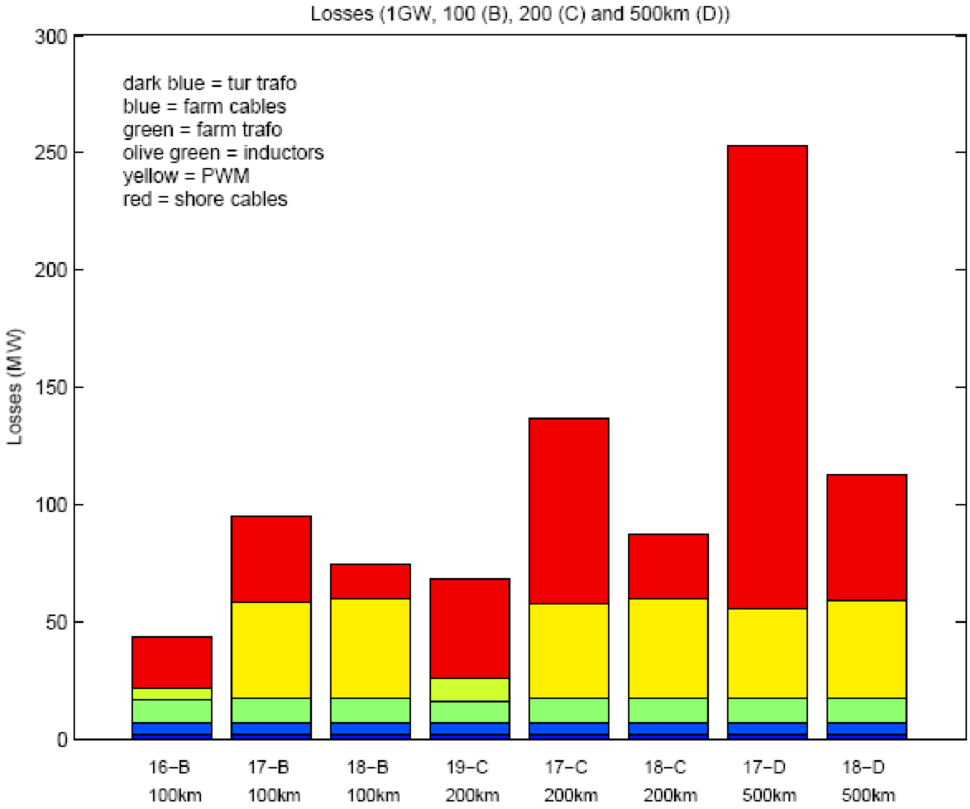


Figure 3.5 Losses at full load in AC and DC transmission system of 1 GW at 100, 200 and 500 km. System 16 = AC, 245kV, system 17 = DC, ±75kV, system 18 = DC, ±150kV, system 19 = AC, 150kV [18]

From the former paragraphs it can be inferred that HVDC systems are favourable for offshore energy transmission at distances above 100-150 km. Then the reactive current limits the power of the HVAC system substantially and lower DC cable losses gain from the extra converter losses.

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 use more and more complicated 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 the to be transported power up over multiple connections will also result in a significant reduction of the system non-availability [18].

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.

Economics

	Type	Distance (km)	LPC (Euro/kWh)
System 16B	AC, 245kV	100	0.0072
System 17B	DC, ±75kV, VSC	100	0.0085
System 18B	DC, ±150kV, VSC	100	0.0067
System 19C	AC, 150kV	200	0.0182
System 17C	DC, ±75kV, VSC	200	0.0114
System 18C	DC, ±150kV, VSC	200	0.0089
System 17D	DC, ±75kV, VSC	500	0.0217
System 18D	DC, ±150kV, VSC	500	0.0158

Table 3.1 Partial levelised production costs (only due to electrical system) for a wind farm of 1 GW at distances of 100, 200 and 500 km [18].

3.6 Conclusions

Up to now all operating offshore wind power plants have a HVAC connection to shore. The first offshore wind power HVDC connection has been realised recently in Germany (Borwin 1 wind farm).

Current submarine HVAC power transmission is economically the best alternative at transmission distances below about 100 km, depending on project conditions. In the near future, semiconductor cost reduction and more stringent grid connection regulations will make VSC HVDC probably also an alternative below 100 km.

At transmission distances above about 100 km HVDC is cost competitive. Current research shows that HVDC LCC is more cost competitive than HVDC VSC but the size and weight of a typical HVDC station and complexity of control during start-up have prohibited its use on offshore platforms. When the cost of the necessary offshore platform and the flexibility are taken into account, HVDC VSC can be the best choice, and the first commercial HVDC transmission systems to an offshore platform is a VSC HVDC system (Troll and Borwin 1). High power offshore generation farms can also contribute significantly to frequency and voltage control of the grid if VSC HVDC systems are used.

New technologies developed in the following fields can be advantageous to the development of offshore renewable energy:

- Submarine transformers, inductors and converters.
- Connection of high voltage static submarine cables to floating platforms.
- HVDC VSC converter loss reduction.
- Service free HVDC technology for submarine locations.
- Cable installation at seabed depths beyond 1000 m.

4 Requirements for Offshore connections

The present and emerging grid connection codes include requirements for [19]:

- Reactive Power Control (RPC)
- Frequency Control and Voltage Control
- 'Fault Ride Through' capability of the wind farm (FRT)
- Operating Margin and Frequency Regulation
- Power Ramping

Reactive Power and Voltage Control

Most network operators require installations to export or import reactive power so that the transmission system is operated as efficiently as possible. The network operator may also, at times, require reactive power to be prioritized to control network voltages within statutory limits.

Offshore wind farms are getting bigger and their number is increasing. They must be seen as power stations. It is becoming essential that wind power stations also contribute to voltage control in large power networks. FACTS (Flexible AC Transmission System) and HVDC devices aim to solutions in this respect. These devices are also necessary to achieve grid code requirements [3].

FACTS devices applied in power systems lead to:

- Increased power transmission capability
- Improved static and dynamic stability
- Increased availability
- Decreased losses.

FACTS technology allows greater voltage and power flow through the power systems.

SVC or STATCOM systems are applied for reactive power compensation in AC transmission systems.

Frequency and Voltage Control: This relates to the ability of an installation to operate over a wide range of frequency and voltage for in general continuous, sustained and short periods.

Fault Ride-Through (FRT): When a network is subjected to a disturbance, it is likely that protection systems will detect and isolate that fault. During this disturbance, a voltage dip or voltage unbalance will occur and it is the requirement of the network operator, that all generating stations above a certain capacity continue operating or ‘ride-through’ the fault. If the fault leads to the successive disconnection of a number of large power stations, a total black-out could occur and it is the intention of the grid operator to prevent this. The network operator also requires the generating station to aid system recovery during the fault by providing network voltage support.

Modern wind turbines are designed to stay connected to the grid during a fault and supply active and reactive power to mitigate the effect of the fault. Low voltage ride through capability is essential in order to maintain system stability.

Operating Margin and Frequency Regulation: The operating margin and frequency regulation are the capability of an installation to operate at a margin below its rated output so that for a significant increase or decrease in frequency it may respond respectively by decreasing or increasing its output. Wind turbines can be designed to incorporate this capability, but this will lead to an overall production loss compared to operation at production maximum.

Power Ramping: A generating station coming on-line, generally operating or going off-line, in terms of power output, can have a significant effect on system dynamics. To ensure that network frequency is not severely affected and control systems are given time to adjust to new operating states it is the requirement of the network operator that generating stations are operated in accordance with specified ramping rates A typical rate of change requirement might be between 1 and 30MW per minute.

Power Quality aspects associated with wind power:

- *Voltage variation*: the influence of a wind farm on the gird voltage is directly related to the short-circuit capacity of the grid. The short-circuit capacity at a given point in the electrical network represents the system strength. If the grid impedance is small (the grid is strong) then the voltage variations will be small.
- *Reactive power compensation and Voltage/Reactive power control*: Locally installed capacitor banks may compensate the reactive power demand of the wind turbine induction generators or line commutated converters. For a wind turbine with self commutated converters, the reactive power can be controlled to minimize losses and to increase voltage stability. For a large scale wind farm, a central reactive power compensation device, such as a SVC (Static Var Compensator) or a STATCOM may be used to provide a smooth reactive power regulation.
- *Flicker*: Fluctuation of the local grid voltage may cause perceptible light flicker. There are two types of flicker emissions associated with wind turbines, during continuous

operation and due to generator and capacitor switching. The flicker caused by a variable speed turbine is considerably less than of a constant speed turbine.

- *Harmonics*: Harmonic disturbances are a phenomenon associated with the distortion of the fundamental sine wave and are mainly produced by power electronic converters.

The power quality requirements can be met by modern wind turbines.

The variation of power infeed for single wind turbine generators depends very strong on the wind profile. Because of the inertia of the wind turbines a smoothing effect can be seen. Nevertheless the variation in the studied high fluctuation wind speed scenario was up to 1.5 MW within 16 seconds respectively 6 MW per minute for a single wind turbine generator.

Because of the dimension of an offshore wind park the power infeed also varies with the location of the single wind turbine generator within the wind park. The superposition of the infeed of all wind turbine generators provided the combined infeed of the wind park. The short term fluctuation is reduced to a mean value per wind turbine generator of 0.18 megawatt in 16 seconds (0.675 megawatt per minute). The HVDC link has nearly no influence to the characteristic of the infeed. It is anticipated that the combination of many offshore wind parks with different locations within an offshore wind park cluster will further improve the smoothing effect.

Summary

The grid connection requirements can be achieved:

- On a per turbine basis via the turbine equipment
- Using mechanically switched shunt reactive elements
- Via co-ordinated control of the turbine equipment and a local OLTC (an on-line tap-changer on the turbine transformer)
- At the point of grid connection using a FACTS application
- Using a combination of the above.
- At the point of grid connection via an HVDC scheme

System studies performed at the feasibility stage of the project should identify the best technical and cost effective solution.

5 Subsea risers and cables

5.1 *Riser:*

1. A pipe through which liquid travels upward.
2. A conduit to transfer materials, power or signals from the seafloor to facilities atop the water's surface, and from the facility to the seafloor. Subsea risers are a type of pipeline developed for this type of vertical transportation. Whether serving as production or import/export conduit, risers are the connection between the subsea and surface facilities.
3. A control line attached to a separate piece of equipment, usually a subsea wellhead, to provide hydraulic or electrical control, or inject small amounts of chemicals.

Umbilical:

An umbilical is a long, flexible construction consisting of tubes, cables, fillers and wrapping contained within a protective sheath [1].
Any of various external electrical lines or fluid tubes which connects one portion of a system to another.

Similar to pipelines or flow lines, risers transport liquids, gases, power or signals. They are usually insulated to withstand seafloor temperatures. Risers can be either rigid or flexible.

Figure 5.1 Onderschrift aanvullen

5.2 *Types of Risers*

There are a number of types of risers, including attached risers, pull tube risers, steel catenary risers, top-tensioned risers, riser towers and flexible riser configurations, as well as drilling risers.

The first type of riser to be developed, **attached risers** are deployed on fixed platforms, compliant towers and concrete gravity structures. Attached risers are clamped to the side of the fixed facilities, connecting the seabed to the processing facility above. Usually fabricated in sections, the riser section closest to the seafloor is joined with a flowline or export pipeline, and clamped to the side of the facility. The next sections rise up the side of the facility, until the top riser section is joined with the processing equipment atop the facility.

Also used on fixed structures, **pull tube risers** are pipelines or flowlines that are threaded up the centre of the facility. For pull tube risers, a pull tube with a diameter wider than the riser is preinstalled on the facility. Then, a wire rope is attached to a pipeline or flowline on the seafloor. The line is then pulled through the pull tube to the topsides, bringing the pipe along with it.

Building on the catenary equation that has helped to create bridges across the world, **steel catenary risers** use this curve theory, as well. Used to connect the seafloor to processing facilities above, as well as connect two floating production platforms, steel catenary risers are common on fixed structures, compliant towers and gravity structures. While this curved riser can withstand some motion, excessive movement can cause problems.

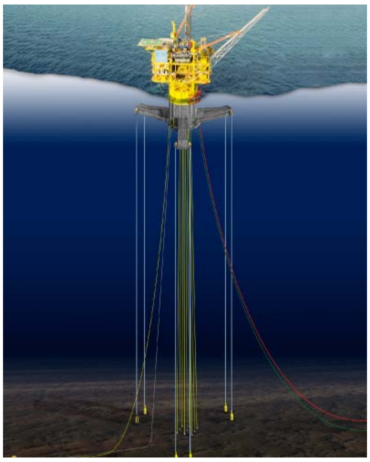


Figure 5.2 Top Tensioned Risers

Top-tensioned risers are a completely vertical riser system that terminates directly below the facility. Although moored, these floating facilities are able to move laterally with the wind and waves. Because the rigid risers are also fixed to the seafloor, vertical displacement occurs between the top of the riser and its connection point on the facility. There are two solutions for this issue. A motion compensator can be included in the top-tensioning riser system that keeps constant tension on the riser by expanding and contracting with the movements of the facility. Also, buoyancy cans, can be deployed around the outside of the riser to keep it afloat. Then the top of the rigid vertical top-tensioned riser is connected to the facility by flexible pipe, which is better able to accommodate the movements of the facility.

First used offshore in Angola at Total's Girassol project, **riser towers** were built to lift the risers the considerable height to reach the FPSO on the water's surface. Ideal for ultra-deepwater environments, this riser design incorporates a steel column tower that reaches almost to the surface of the water, and this tower is topped with a massive buoyancy tank. The risers are located inside the tower, spanning the distance from the seafloor to the top of the tower and the buoyancy tanks. The buoyancy of the tanks keeps the risers tensioned in place. Flexible risers are then connected to the vertical risers and ultimately to the facility above.

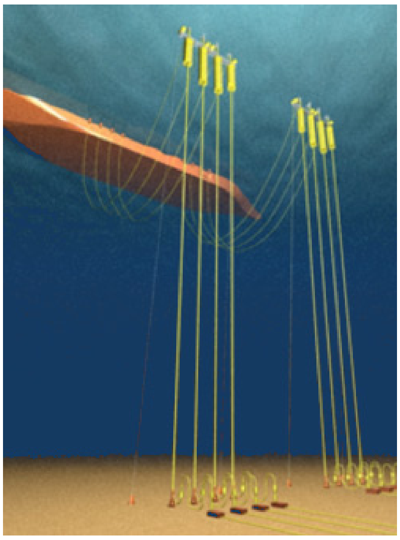


Figure 5.3 Hybrid Riser System

This is a hybrid system that can accommodate a number of different situations, **flexible risers** can withstand both vertical and horizontal movement, making them ideal for use with floating facilities. This flexible pipe was originally used to connect production equipment aboard a floating facility to production and export risers, but now it is found as a primary riser solution as well. There are a number of configurations for flexible risers, including the steep S and lazy S that utilize anchored buoyancy modules, as well as the steep wave and lazy wave that incorporates buoyancy modules.

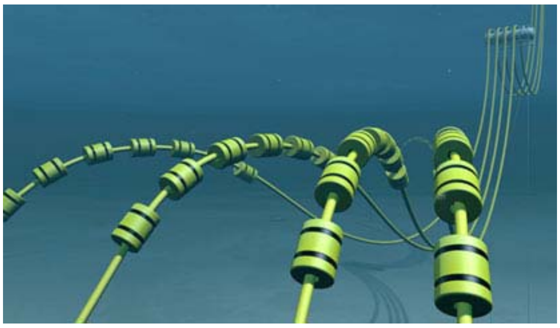


Figure 5.4 Buoancy Modules

5.3 *Electrical cables*

Figure 5.5 Onderschrift?

The electrical power generated by any Offshore Device must be carried to shore in such a way as to minimise cable costs and power losses. The most efficient means of power transfer is at high voltage, and this will generally involve cables since overhead lines require a structure to suspend the lines.

AC cables require reactive power compensation, the amount depends on the length of the cable. The two options for HV transmission are HVAC and HVDC.

One of the most important items in the design of a submarine transmission system is the choice of cable type [1]. The type of cable directly affects the cost of the system and its installation. Tides and currents, soil stability, seismic activity and trawling and anchorage in the zone may influence the cable type. Today submarine high voltage cable manufacturers are found only in Europe and Japan. Some of the most important manufacturers are Prysmian (previously part of Pirelli), ABB, Nexans, Sumitomo and Hitachi.

Submarine cable components:

Conductor core: The current carrying capacity depends on the line voltage, rated power, cable length, isolation method, burying depth, soil type and electrical losses [11]. Current carrying capacity can be increased by using a conductor cross section of up to 2000mm^2.

In HVAC transmission system it is advisable to join the three-phase cores in a single cable, and sometimes two core cables are used in HVDC applications. By doing so, cable and installation costs are reduced and lower electromagnetic fields and induced current loss than using separate cables are obtained. The main disadvantage is that multi-core cables requires a bigger number of intermediate joints and they are rated to lower power than separate cables.

In HVDC cables, the path for current return may be the earth electrode water or even low voltage cables, thus saving one cable core, depending on the environmental regulation because of some chemical reactions taking place at the electrodes.

Figure 5.6 Submarine cable types

Figure 5.6 shows submarine cable types [1]:

(a) LPFF cable (courtesy of ABB);

(b) MI cable (courtesy of Prysmian);

(c) three-core XLPE ac cables (courtesy of Prysmian);

(d) one- and three-core XLPE DC cables (courtesy of Prysmian);

(e) cable with optic fibre (courtesy of Sumitomo).

Electrical insulation: Electrical insulation is characterized by the material (oil impregnated paper or plastic) and the manufacturing method (paper sheets or extruded plastic). There are several long-distance submarine cable types. Historically, and up to now the most common cable type is cellulose paper impregnated in synthetic or mineral oil. Low pressure oil filled (LPOF) can be built with transmission distances up to 50 km, longer distances are not possible because of the impracticability to maintain oil pressure.

Insulation screen. A layer of paper or extruded polymer around the insulation reduces electric field strength and field concentration zones. Also a better fixation of the insulation and the core is obtained.

Metal sheath. In the outer face of the insulation screen of each core a metallic sheath connected to earth is used as a path for fault currents if the cable is damaged by an external cause. This sheath is also a barrier for water. In ac cables the sheath carries induced currents and losses are generated.

Armature. Cables are covered with an outer metallic armature that provides mechanical strength with anti corrosion protection. Sometimes a repellent is used to avoid damage by marine fauna. This armature is formed by galvanized steel wires.

Optic fibre. Optic fibre can be inserted in the cable for communications, cable monitoring, etc. In this case the temperature of the cable may be limited to avoid damage in the optic fibre.

Protecting sheath. A final propylene sheath is used as the final outer protecting layer.

5.4 HVDC cable

One cable could be two conductor and bipolar, while two cables could be monopolar (one conductor at practically zero voltage). In case of a monopolar single cable, the return current flows through the ground or sea. While reducing the cost of the cable and its installation, single pole single cable transmission can create stray currents that may lead to corrosion on nearby metallic structures and sea electrodes generate large amounts of harmful chlorinated compounds.

A bipolar system is the more common design, but often back-up sea electrodes are included for temporary use in the case of damage of one of the cables. Recent developments in cable technology mean that it has become possible to operate in bipolar mode using only one cable. A monopolar coaxial cable has recently been developed with the return conductor surrounding the main conductor, outside the lead sheath thus obtaining the advantages of the monopolar system without the drawbacks.

DC cables themselves are less expensive than AC cables, because for a given amount of insulation and conductor material DC cables can be operated safely at higher currents, therefore allowing more power per cable. However, the costs of the power converters (inverter and rectifier) at either end of the transmission line are considerable.

In DC cables the voltage distribution is dependent on the geometry of the cable and highly dependent on the temperature drop across the insulation, as the conductivity of the insulation material increases exponentially with temperature. Therefore, there is a direct correlation between the conductor losses and the electrical stress distribution in the insulation in a load carrying cable. Usually it is the design stress and not the maximal allowable conductor temperature that limits the transmission capacity of a DC cable.

The various unavoidable capacitive aspects count against AC installations, while DC equipment is hampered by the expense of converters. A decision between the two schemes can only be made by evaluating the total cost (including cable laying costs) of each.

5.5 Connecting cables and floating platforms

Ocean energy systems are either floating systems or systems fixed to the sea bed. In case of a sea bed fixed system often J-tube raisers are used to connect the power cable from sea bed to the system.

Connecting floating devices, like floating ocean energy devises or floating wind energy structures (Hywind) is less trivial. The dynamic section of the cable is subject to substantial forces due to waves and ocean currents, and in the case of a floater to the motion of the floater itself. A standard cable is not ready to withstand this type of load, mainly because of the low fatigue resistance of the shield around the core. Communications with cable manufacturers [14] shows that cable motion and stresses are input for the marine cable dynamic design process to cope with the fatigue loads encountered during the life time of the cable. Special hang-off constructions have to be used between floating structures and marine cables. It was mentioned that in this case lead sheath will not be used in such a cable design.

6 Wind energy grid integration studies

This section summarizes results of recent grid integration studies realised in Europe. Wind energy grid integration studies investigate:

- Wind power plant capabilities: methods to enable wind power plants to provide services and to offer characteristics similar to conventional power plants.
- Grid planning and operation: sustainable enlargement of the transmission capacity and enhancement of the utilisation of the grids to allow large-scale deployment of wind energy technology
- Wind energy and power management: tools and business models (markets) to allow economic wind power utilisation
- Here short summaries are presented of the main Wind Energy Grid Integration Studies.

6.1 TradeWind [21]

The TradeWind project, financed under the EU's Intelligent Energy-Europe (IEE) Programme, was a European project which dealt with issues regarding reliable integration of large amounts of wind and the impacts of such integration in the trans-European power markets. The project lasted from November 2006 until February 2009 and had as research focus the analysis of cross-border power flows derived from increasing wind power penetration scenarios in Europe [22]. The TradeWind project spanned 8 different European countries and 8 work packages distributed over 3 phases: preparatory phase (WP2-4), simulations and analysis (WP5-7) and recommendations (WP8). The study time horizon, which included short, medium and long term scenarios, was targeted until the year 2030. The medium term scenarios chosen were 2008, 2010, 2015 and 2020, while the 2015 scenario was chosen in order to allow for comparison with the EWIS study. The emphasis of the TradeWind study was on institutional, market, and regulatory aspects. Therefore, even though the modelling included technical aspects of wind integration, it did not have as a primary objective the making a detailed grid design for offshore WPPs. The study concludes that an offshore grid can be a solution and could be economically beneficial when considered at a European level and recommends that further studies should focus on more thorough planning and optimization of offshore grid solutions in the North and Baltic Seas.

6.2 EWIS [21]

The European Wind Integration Study (EWIS) studies integrating large amounts of wind energy, onshore and offshore, at a pan-European level, analyzing all synchronous areas within Europe. The study, which lasted for almost 3 years, was initiated by the European Network of

Transmission System Operators for electricity (ENTSO-e) in association with its stakeholders in June 2007. In total 13 different European countries were involved in the project. The technical part of the study was finalized in October 2009 and its final report published at the end of March 2010 [23]. On a technical level the project was split in 6 work packages: Present Situation and Market Aspects, Scenarios and Exchange Schedules, Power System Analysis, Operational Aspects, Cost Analysis and Legal Aspects, and Communications. The main research focus of EWIS was on how to efficiently accommodate wind generation from a market and TSO point of view, ensuring electrical energy supply remains safe given wind unpredictability. The study demonstrated that the necessary costs for network reinforcement are to be overcome by the benefits of wind energy generation, even though, in absolute terms, these costs are expected to be significant. The time horizon of EWIS was until 2015, for which the study provided detailed analysis of power flows inside the ENTSO-e network as well as dynamic system behaviour, for the different wind penetration scenarios. EWIS results can be a valuable starting point beyond the 2015 time horizon for future detailed investigations of offshore WPP clusters and suitable offshore grid infrastructure concepts.

6.3 Offshore Grid [21]

The OffshoreGrid project [24], funded similarly to TradeWind via the EU-IEE programme, is among the most recently started research projects with respect to offshore electricity infrastructures. It aims to provide recommendations for policy makers as well as TSOs concerning technical, policy, and economic aspects related to building a transnational offshore grid. In particular, the project targets to be used as input for fulfilling the European Unions electrical infrastructure objectives stated in the Second Strategic Energy Review, which includes the development of a Baltic interconnection plan, a blueprint of a transnational electricity grid in the North Sea, and the completion of the Mediterranean ring.

The initial focus will be on Northern Europe while the obtained results will be used to include the Mediterranean area into the study at a later stage. The Offshore Grid project has started in May 2009 and is foreseen to finish by end 2011. It is executed by a consortium of European research centres, universities and consultancy partners [25].

The project is set up by preparatory work packages and technical-economic work packages. First, the current state of the regional electricity markets is being assessed by comparing market integration and coupling, fuel costs, CO2-price scenarios, and installed conventional generator capacities. Second, realistic wind generation scenarios are developed for the Baltic Sea and North Sea countries for 2020 and 2030, containing high-resolution wind power generation time series.

Subsequently, prototype networks of fundamentally different topologies are provided to illustrate the connection arrangement of future transnational offshore interconnectors: shore-to-shore, meshed, cluster with multi-way interconnector (similar to the Kriegers Flak study) and a combination of interconnectors and meshed grids. These prototype grids form initial conditions for the technical-economic analysis, which consists of design optimization by considering technical constraints such as bottlenecks in the transmission grid and availability of technology as well as the corresponding investments costs, and economic issues such as (offshore) market consequences [26].

6.4 IEA Wind Energy Task 25

The (IEA) Wind Energy Task 25: Power Systems with Large Amounts of Wind Power is an international forum for the exchange of best practices regarding the integration of large scale wind energy into power systems. The main focus is on technical-economic feasibility (inclusion into electricity markets, grid expansion costs, reliability, capacity credit), the assessment of technical constraints (grid stability, reserve requirements) [27], and sharing information on used methods.

The first phase of IEA WE Task 25 started in 2006 and in 2008 it has been decided to continue with a second phase until 2011. In the final report of Phase 1 [28] the IEA WE Task 25 recommends the transition towards a more flexible electricity grid, which includes management of generation and demand, larger balancing areas, more interconnection capacity, better integration of markets, and utilizing the improved controllability of future wind power plants.

IEA Task 25 [20] concludes on reserve requirements:

- The highest reserve from a study where four hour variability of wind (not forecast error), combined with load forecast error: 15 % reserve requirement at 10 % penetration and 18 % reserve requirement at 20 % penetration of gross demand (UK)
- German Dena study – with similar methodology results in 15-20 % reserve requirement for day-ahead forecast errors of wind power
- With the latest wind power prediction tools, the variability of wind power also 2-4 hours ahead can be considerably forecasted
- How wind power is taken into account in the operational practices of TSOS is crucial at high wind penetration levels

In most cases, the current conventional capacity is able to supply the balancing power and no new reserve capacity is needed in the system

- In all cases, an increase in the use of short term operating reserves are seen This is also the experience of integrating wind power in Denmark and Spain
- Different power systems experience different costs, depending on their flexibility
- Larger balancing areas results in a reduced need for balancing power and better resources for balancing (potential balancing through interconnection).

IEA Task 25 concludes on wind power impact to electricity markets – day ahead markets:

- Wind power production bids according to forecasts
- Lowers market price when a lot of wind available resulting in more volatility to prices, low wind / high wind days
- Long term, average prices can stay the same if other generation capacity changes
- Challenges
- flexibility of conventional capacity in the time scale day/half day ahead.. wind can push conventional capacity out of markets
- adequacy of power has to be secured

IEA Task 25 concludes on Grid reinforcements:

Building a grid for the total wind power amount is often significantly more cost effective than upgrading bit by bit.

Difficult/lengthy building permits is an incentive for improving the existing network efficiency and utilization:

- by using online monitoring (temperature, wind, loads, etc),
- by introducing new components as FACTS and phase shift transformers;
- by upgrading degraded components as cables, lines, protections and transformers
- by accepting occasional wind curtailments

IEA Task 25 concludes on transmission planning for wind power:

- Transmission is recognized as a key enabler to reach renewable energy goals and carbon reduction goals
- Wind energy is different from conventional energy and requires a different approach to transmission planning.

European wide efforts:

- ENTSO-E first Ten year network development plan
- EC Energy Infrastructure Package - first outlook on a blueprint for offshore grids in Northern Europe.

7 State of the art ocean energy grid integration

7.1 Introduction

Beside offshore wind energy ocean energy systems are successfully deployed at many location in Europe. Five forms of ocean energy renewable energy sources are distinguished in [31, 32]: Tides, waves, ocean current, temperature gradient and salinity gradient.

The resource potential is considerable. Dedicated systems have been designed and deployed at several location; mostly in coastal areas. Up to now most of these system are experimental and many different prototypes are built [31]. Most of the system power levels range between kW size and hundreds of kW's size. Industry is working hard towards commercialisation.

However in [12] it is mentioned that installation and operation of large-scale grid connected ocean power plants, consisting of modular energy conversion units, still need to overcome significant technological and knowledge barriers.

This section gives an overview the different ocean energy devices and test locations with emphasis on the applied electrical systems and its connections to the grid.

7.2 Grid Connected Ocean Energy Infrastructures

Apart from EMEC, a number of different institutions and organizations across Europe have been funding similar projects to build testing infrastructures for marine energy converters. Grid-connected facilities will be installed in Cornwall (UK), in the Basque Country (Spain), at Figueira da Foz (Portugal) [33] and at Frenchport (Ireland) [34].

Figure 7.1 A view of the EMEC test site at Orkney

Open Sea Test Facilities

1. EMEC

EMEC (European Marine Energy Test Centre), as mentioned in [29], is the forefront of the development of marine-based renewable energy technologies that generate electricity by harnessing the power of ocean waves and tidal streams. It is located near the Hoy Mouth of Orkney.

It includes two installations of testing: one for wave energy convertors, at Stromness in operation since October 2003, and one for tidal energy convertors.

Developers of wave and tidal energy devices install their moorings, connect the subsea cable and their marine energy device. The cables are connected to the grid in a coastal 11 kV control and switching station.

A complete operational monitoring system is available. A purpose built weather station is close to the test site; and wave rider buoys are deployed to access the wave characteristics.

The wave testing site is located near Stromness on the Orkney Islands in Scotland.

Its principal characteristics are:

- Testing zone placed to between 1 and 2 miles from the coast and at a depth of 50m
- 4 berths of 2,2 MW capacity. Total power of 8,8 MW
- Every berth is directly connected to a substation in land across one cable of 11kV
- Secondary substation (from 11 to 33 kV) close to the coast
- Maximum power feeding to the grid: 7MW

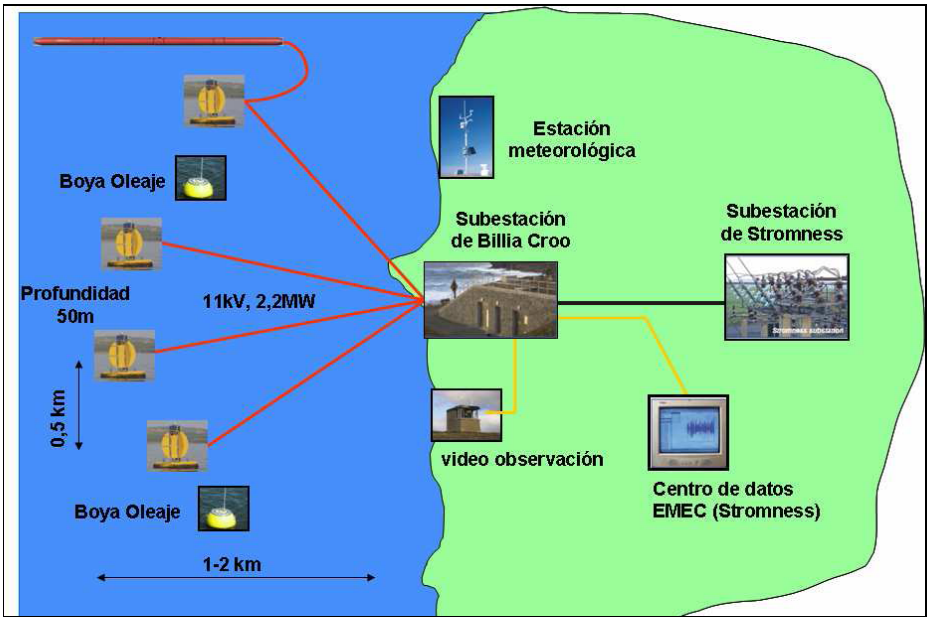


Figure 7.2 EMEC wave testing site lay-out [29]

The principal characteristics of the tidal site:

- Located close to Eday, on the Orkney Islands in Scotland.
- Area of 2km times 3,5 km
- Water depth between 25 and 50m
- Tidal flow of 3,5m/s - 5 berths of 5 MW each one. The total power is 25 MW
- Every berth is directly connected across a cable of 11kV and 5MVAs (135mm2) to the substation
- Secondary substation (from 11 to 15 kV) close to the coast
- Maximum power feeding to the grid: 4MW

Figure 7.2 and Figure 7.3 [29] show respectively the lay-out of the EMEC wave and tidal testing site.

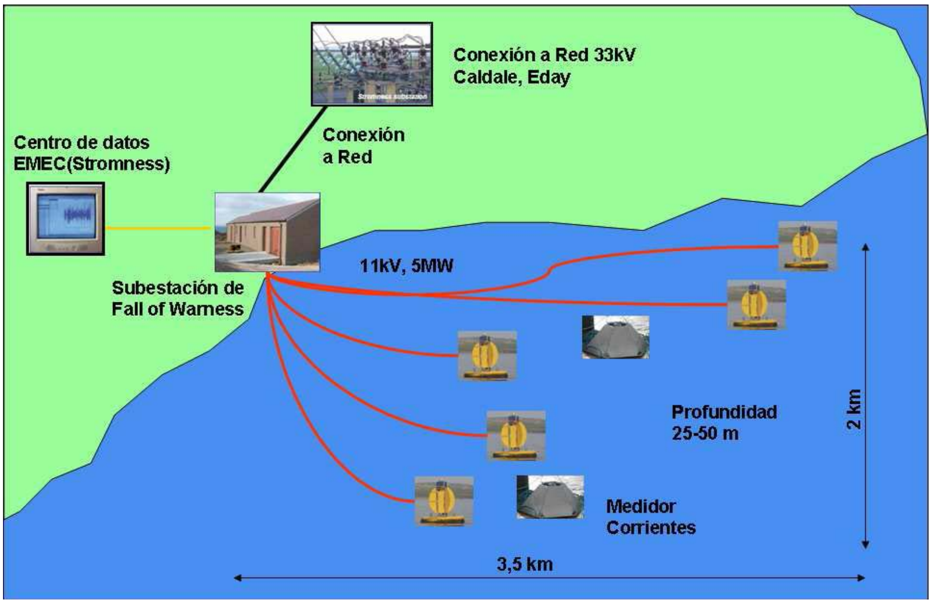


Figure 7.3 EMEC tidal testing site lay-out [29]

2. North Coast of Cornwall UK

In [4] a study on an array of different offshore wave energy conversion devices using a power generation system designed to create an efficient facility for grid power integration has been presented. The power generation system consists of a 10-miles sub-sea cable and a distribution unit connected to four different wave energy devices. This example should be of assistance in finding electrical connection configurations for WECs. The results from this model will allow for the analysis of simple wave farm set-ups. Arrays can then be investigated to reduce power output fluctuations and improve the whole power generation efficiency to take advantage of arrays.

Included in this model are:

- an Archimedes wave with a linear generator,
- an Oscillating Water Column OWC;
- a Pelamis with induction generator;
- a Dragon with Permanent Magnet generator.

The grid integration of the OWC or the Wave Dragon uses full-scale power electronics. A power electronics interface provides excellent controllable characteristics for these devices. The model was developed to analyze the effects of the offshore wave farm on the electrical network to which it is connected.

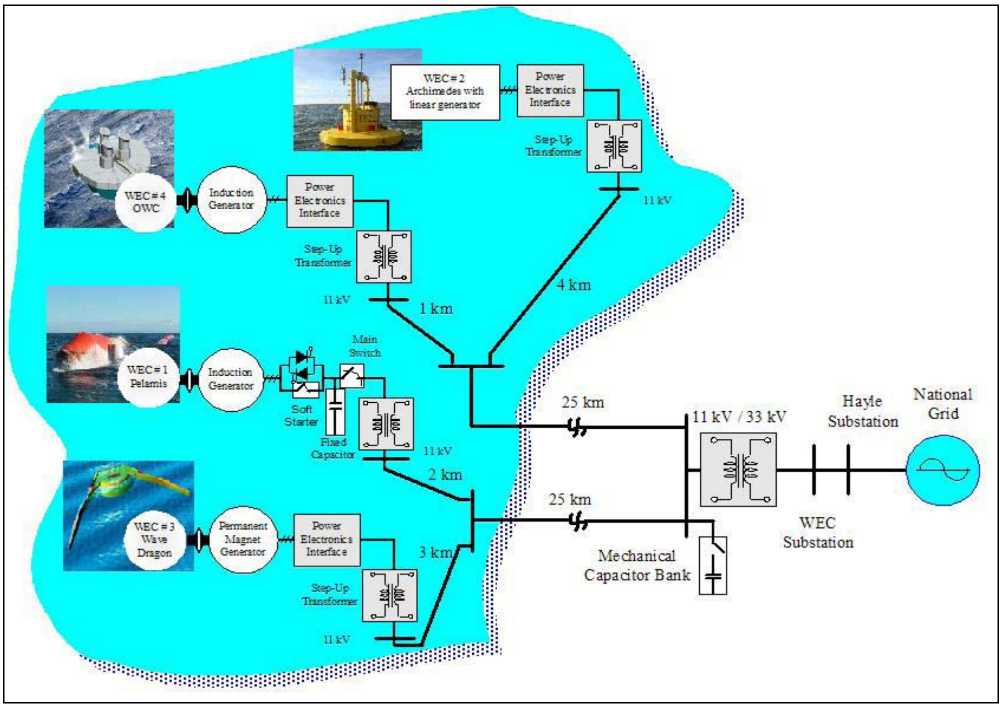


Figure 7.4 Single-line diagram of the commercial development for grid integration of multi ocean wave energy conversion devices [4].

In MatLAB simulations in [4] the model study showed the effect of the wave energy array power factor on the voltage rise and reactive power compensation requirements. It also showed the effect on the system efficiency and cable losses.

Within the **Wave Hub project** [29, 36] will build an electrical grid connection point 12-15 km offshore to which wave energy devices will be allowed to connect. It will provide a well-defined and monitored site with electrical connection to the onshore electricity grid and will greatly simplify and shorten the consents process for developers.

Its principal characteristics are:

- The occupied area is 2 times 5 km, 10 nautical miles to the north from St. Ives. It consists of an electrical hub on the seabed 16 kilometers off the north coast of Cornwall, off the Hayle's coasts, South West England to which wave energy devices can be connected.
- Water depth is between 50m and 65m.
- The 12-tonne hub is linked to the UK’s grid network via a 25km, 1300 tonnes of subsea cable operating at 11kV. Submarine Hub Capacity of 20 MW.

- The project holds a 25-year lease for eight square kilometers of sea with an excellent wave climate. Wave Hub has the necessary consents and permits for up to 20MW of wave energy generation and offers a clearly defined and fully monitored site for marine energy production.
- Four separate submarine transformers of 11/24 kV are available to lease, each with a capacity of 4-5MW.
- Onshore substation with single connection point to the Hub.
- 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.
- The wave Hub needed a budget of £ 42M.

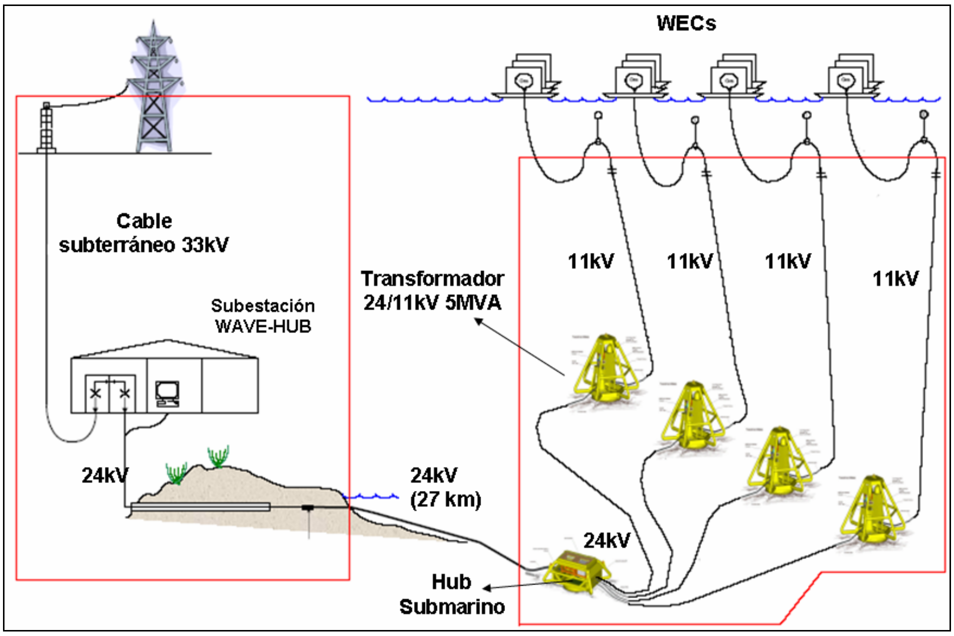


Figure 7.5 Wave hub electrical connection lay-out

Figure 7.6 Pieces of Wave Hub are installed on the seabed following a delicate operation to lower the hub into 55 meters of water, 10 miles off Hayle, in Cornwall.

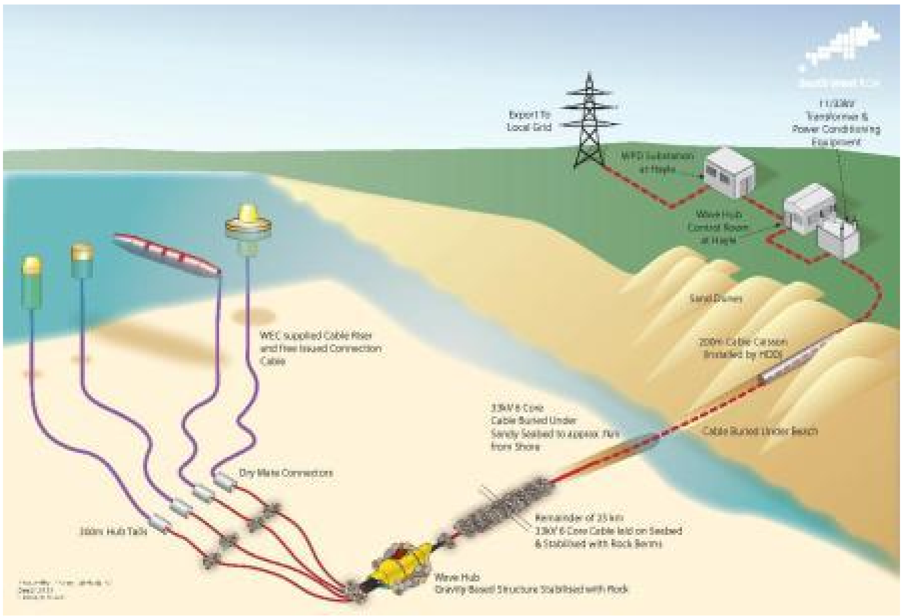


Figure 7.7 In this image the Wave Hub is shown schematically.

Wave Hub is complemented by the Peninsula Research Institute for Marine Renewable Energy, a centre of excellence delivering world-leading research, facilities and technology transfer in marine energy, excellent port infrastructure and an established supply chain in South West England.

3. Biscay Marine Energy Platform (BIMEP)

The BIMEP [29, 36] project results in infrastructure for research, demonstration and operation of offshore wave energy converters (WEC), which aims to place the Basque Country at the forefront of marine energy and create a technological and industrial sector around this energy. The project started in 2007 as a conceptual study and selection of potential locations.

The project is now carried out by EVE (Ente Vasco de la Energia) and BIMEP is planned in Armintza, about 20 km north of Bilbao. The plan is shown in figure xx and has the lowing characteristics.

- 4 incoming lines of 13 kV and 5 MW between offshore junction box and onshore cable joint.
- 13/30 kV and 20 MW transformer.
- Connection to a 30 kV electric power line.
- Electrical measurement systems for each incoming electric line.
- Water depth between 50 - 90 m.
- The closest point to land is 750 m.
- Total power capacity 20 MW.
- 4 test berths or power connections
- units of 13 kV and 5 MW.
- Each berth connected to the onshore substation via a subsea cable.
- Berths designed to make connection/disconnection of WECs easy.
- Onshore substation.
- Research and data centre.
- Onshore Electrical Installation: From the subsea cable entry point to land to the substation (4 x 13 kV/ 5MW) and from there to the power grid (30 kV/ 20MW) connection.

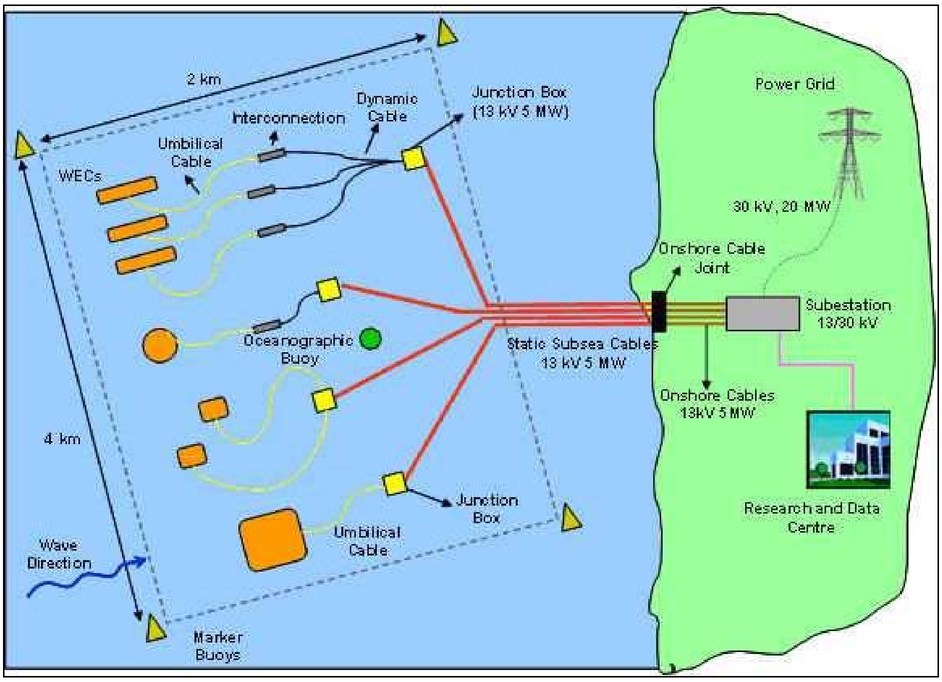
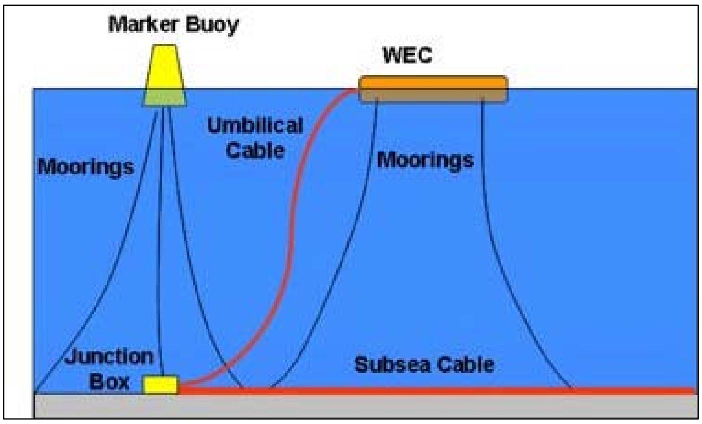


Figure 7.8 Schematic overview of the BIMEP system



System Elements:

- Marker Buoy
- Junction Box
- Connectors
- Umbilical Cable

Figure 7.9 Detail of connection of WEC to Junction box and subsea cable

Planning of this project

The installation work is planned to start in summer 2011. In November 2009 the property engineering tender was awarded to the Bask Engineering company SENER.

7.3 Summary

To summarize the current status of the ocean power sector, with regard to their challenges, opportunities and grid interconnection issues, the following key observations can be put forward, according to [12]:

- Most of the ocean wave and tidal current technologies are at early stages of development. Only a few of the devices have been tested in grid-connected mode and the duration of such tests has been relatively short. The power range of wave and tidal devices is in the rage of a few hundreds of kW's. On the other hand offshore wind power is already operating in Wind power stations in the range of hundreds of MW's.
- All known offshore wave and tidal current experiments have been grid connected via an AC subsea cable; running on a relative low voltage 11- 24 kV.
- Resource and experimental performance data would facilitate device modelling and characterisation. These models (dynamic and steady-state) could be used in subsequent system studies to identify electrical network impacts.
- Greater predictability of ocean wave and tidal current resources may appear as a unique advantage of ocean renewable technology. However, methods for resource forecasting need to be realised and integrated with plant operation.
- Short-term energy storage inherent in several converter systems may reduce the effects of high frequency resource variability. State-of-the-art technologies such as DFIGs, power electronics and multi-pole permanent magnet generators could play an important role.
- Optimum configurations of multi-unit/multi-farm ocean energy plants and their impact on electrical networks need to be understood.
- Design of offshore electrical networks and realisation of remote operation and control will play a key role in realising reliable grid integration of ocean power plants.
- Detailed investigations need to be carried out on a case-by-case basis. Such studies should accommodate various site-specific features (resource, network, load and (generation) and device-specific characteristics (steady-state and dynamic performance models calibrated with test results).
- In the future wave and tidal current power hopefully can take advantage of the offshore wind electrical infrastructure.

In a very general and subjective manner, it can be stated that grid integration of ocean energy systems will encounter similar challenges that were prevalent in the wind energy domain and especially the offshore wind sector. Further consideration of the needs and concerns put forward by various stakeholders (electric power utilities, technology developers, environmental regulators and other public bodies) should also be considered in order to identify the system-wide repercussions of bulk ocean power harnessing. As this area of research, development and demonstration accumulates further operational experience, solutions to many of the expected challenges will evolve. In addition, knowledge sharing and interaction within multiple disciplines of engineering practices,

scientific research and policy discussion will aid the process of ocean energy's emergence as a viable industry. [12]

8 State of the art offshore oil and gas industry electrical systems

8.1 TROLL platform

Alegria [1]:

The electrical power demand of offshore platforms for the oil and gas industry is usually provided by inefficient gas turbines with high emissions of carbon dioxide. A considerable reduction in carbon dioxide emissions is obtained when electrical compressors with power supplied by the onshore electrical grid are used. A first attempt to reduce carbon dioxide emissions at offshore platforms by this method is the Troll Gas station in Norway.

Today power of 10–100MW is needed in small oil and gas fields and power above 100MW is used in big fields such Ekofisk or Tampen of 500MW [4].

Besides HVAC transmission, HVDC transmission has also been used in at least one gas field in the North Sea. Since 2005 the compressor in the Troll platform is powered by a HVDC system of 60 kV, with a transmission distance of 70 km and a power rating of 84 MW.

Onshore the system is connected to the 132 kV transmission grid and the offshore platform grid has a voltage of 56 kV. The main difference between the oil and gas industry and marine power is the benefit margin. Costs differences that are negligible in the oil and gas industry may be the difference between success or failure in a marine power project.

Figure 8.1 Troll HVDC Light® cable, triple extruded polymer insulation system

Troll A Precompression project Kollsnes -Troll A, Norway; west of Bergen (N)

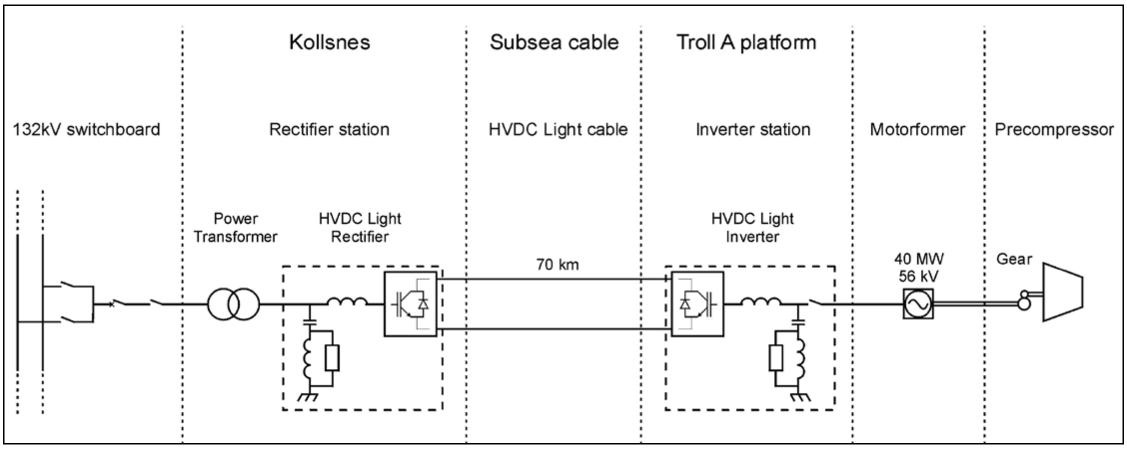


Figure 8.2 Simplified single-line diagram showing HVDC Light® rectifier at Kollsnes, cables transmitting the energy to Troll A Platform, HVDC Light® inverter on Troll A and Motorformer motor driving the compressor. Two parallel systems will be installed during phase 1.

Main data

Rated power 2x40 MW
DC voltage ±60 kV
AC system voltage 132 kV
AC motor voltage 56 kV

AC filters
Kollsnes: 39’th and 78’th harmonic
Troll A: 33’th and 66’th harmonic

IGBT valves
Valve type Two level
Cooling system Water
IGBT type 2,5 kV/500 A

Cable
Type Triple extruded polymer
Cross section 300 mm2
Length 4 x 70 km

Transformers (Kollsnes only)

Type Three-phase, two winding
Rated power 52 MVA

8.2 *Electrical connection of units to Beatrice field*

In 2007 two Repower 5M wind turbines were installed near the Beatrice Alfa Oil Rig in the Murray Firth north of Aberdeen.
The two WTG units ('A' and 'B') are linked by a 900m long 33KV electric cable, about 100mm diameter, depending on the amount of armour protection selected during detailed design. The cable is buried in the seabed sediment to a depth of about 1m.

WTG unit 'A' is linked to the Beatrice AP platform by 1,900m long 33KV electric cable, which would also be about 100mm in diameter and probably buried. Figure 3-5 shows the planned routes of both cables.
Beatrice AP is already linked to the mainland by a 33KV subsea cable that runs to the Scottish and Southern Energy (SSE) substation at Dunbeath (Scotland). This cable is buried to a depth of about 1m and is used to provide some of the power required on the Beatrice AP, AD and B platforms.

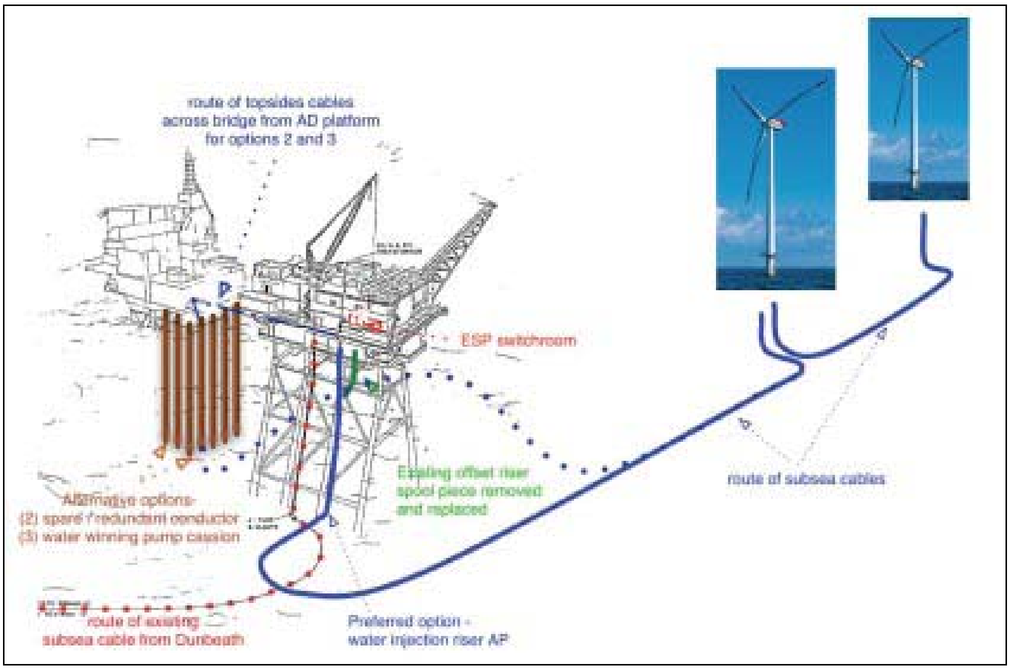


Figure 8.3 Locations of the wind turbines and electrical cables at the Beatrice AP platform.

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10 List of Abbreviations

AC	Alternating current
CSC	Conventional (thyristor-based) current Source Converter
CSI	Current source inverter
DC	Direct current
DD	Direct Drive; wind turbine without gear box
DSO	Distribution system operator
EDLC	Electric double-layer capacitor
EU	European Union
EWIS	European wind integration study
FACTS	Flexible AC Transmission System
HV	High voltage
HVDC	High voltage DC
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronic Engineers
LCC	Line Commutated Convertor
LPZ	Lightning protection zone
LV	Low voltage
MCC	Mutually Commutated Converter
MPP	Maximum power point
OLTC	On Line Tap-Changer
PCC	Point of common connection
PMSM	Permanent magnet excited synchronous machine
POC	Point of connection
PV	Photo voltaic
PWM	Pulse width modulation
SEIG	Self-excited induction generator
STATCOM	*Static Synchronous Compensator*
SVC	Static Var Compensator

TFM	Transversal flux machine
THD	Total harmonic distortion
TSO	Transmission system operator
UCTE	Union for the coordination of Transmission of Electricity
VHV	Very High Voltage
VSC	Voltage source convertor
VSI	Voltage source inverter
WEC	Wave Energy Convertor
WES	Wind energy system
WT	Wind Turbine