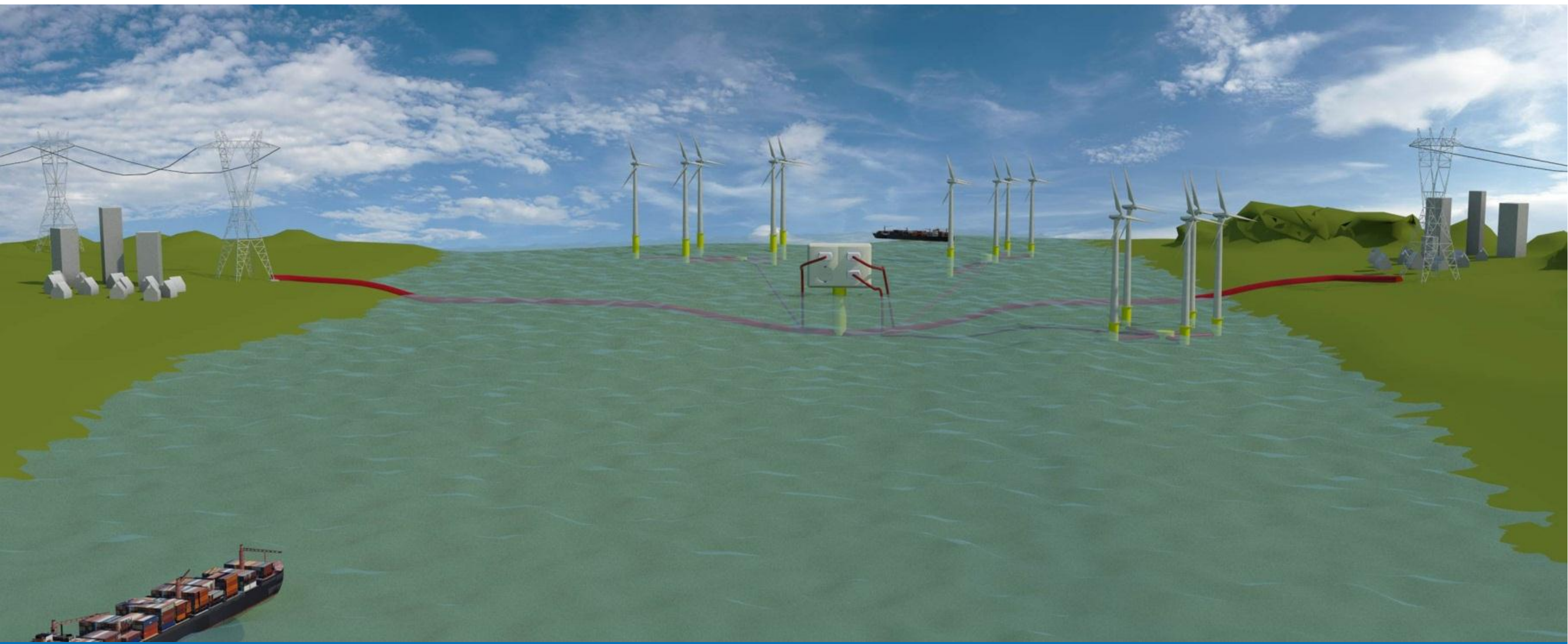

Synergies at Sea
Feasibility of a combined infrastructure for offshore wind and interconnection

Appendix B1: Technology Review

Authors: ECN, Delft University of Technology

Date: 5 November 2015

Synergies at Sea is a consortium that investigates the feasibility of an innovative electricity infrastructure on the North Sea. The consortium examines technical solutions, changes to international legislation and regulations and new financing models. The consortium consists of Nuon/Vattenfall, ECN, RoyalHaskoningDHV, Groningen Centre of Energy Law of the University of Groningen, Delft University of Technology, DC Offshore Energy and Energy Solutions, and is coordinated by Grontmij.

Technology review for the TKI-SaS Scenarios

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The Netherlands - October 21, 2013

Report summary

Title:	Technology review for the TKI-SaS scenarios

Prepared to:	

Prepared by:	

Abstract:	A preliminary study about the technology feasibility of a trans-national connection between UK and the Netherlands via two offshore wind farms planned in each of these countries is presented in this report. The main aspects concerning HVAC and HVDC technologies are addressed and fourteen different possible connections which represented each of technical scenarios are studied.

Classification	Preliminary- Confidential

Pages	92

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Contents

List of Figures

List of Tables

1. Introduction

In 2010, power plants using gas, coal or fuel oil represented 56% of all Europe's installed power [16]. However these energy resources have two major problems: they are not renewable in the human time scale and are highly pollutant. Moreover, the economic growth that is happening in developing countries, e.g. China and India, requires an increasingly consume of oil, making the reserves more disputed. Additionally the population is growing, especially in developing countries, therefore the required energy needs will increase and so will the oil prices [17].

With this background, several countries are making large investments in alternative energies. The usage of renewable energy sources, such as wind, solar, hydropower, biomass, wave, tides and geothermal heat, has experienced rapid growth in the last decade. The already expired Kyoto Protocol was the first international agreement between nations to mandate country-by-country reductions in greenhouse gas emissions, which were binding under international law. The European Council adopted new environmental targets even more ambitious than that of the Kyoto Protocol known as the Climate Action or the “20-20-20” targets with the following three key objectives for 2020 [18]:

- 20% reduction in European Union (EU) greenhouse gas emissions from 1990 levels;
- 20% share from renewable resources in the EU's energy consumption;
- 20% improvement in the EU's energy efficiency.

Achieving these ambitious targets is a difficult task; nevertheless the transition to renewable resources will produce an economic growth and a generation of new jobs while it ensures environmental protection [19-21].

1.1. Wind Energy

One of the most utilized renewable energy sources is wind energy [16]. In Europe, onshore wind energy technology is already a mature technology, since it has been largely installed throughout the last years. Indeed, the onshore wind energy market has grown in Europe in the past decade at an average pace of 33% [22], while worldwide the growth rate was of around 25%, with the total installed power reaching 159 GW at the end of 2009 [23]. However, suitable places onshore are becoming rare. Therefore, countries are now starting to install wind turbines offshore, where space is more abundant and the wind has higher mean speeds, since there are no obstacles in the open sea (see Figure 1).

In the last decade, the growth of offshore wind energy production and its share in the total electricity production rapidly increased [4][24]. Figure 2a shows the yearly installed and accumulated offshore power installed around the world. In Figure 2b, it is possible to see the location of the operational, or under construction, offshore wind farms in the north of Europe.

Figure 3a shows the distribution of offshore wind farms per location. Most of the most of the projects are located in the Northern part of Europe: out of the 76 projects, 48 are located either in the North, Irish or Baltic seas. The North Sea with 31 farms is the offshore location with the highest number of projects. Figure 3b shows the distribution of the offshore projects per country. As expected, the highest share of offshore projects belongs to the Northern European countries. The United Kingdom leads with 22 installed, or under construction, offshore projects, followed by Denmark with 13.

The predictions for the offshore wind energy are that 150 GW of offshore wind power will be in operation, by 2030, from more than 100 offshore wind farms only in the North Sea [24][25]. Hence, to meet the predictions, an enormous amount of wind turbines will have to be installed

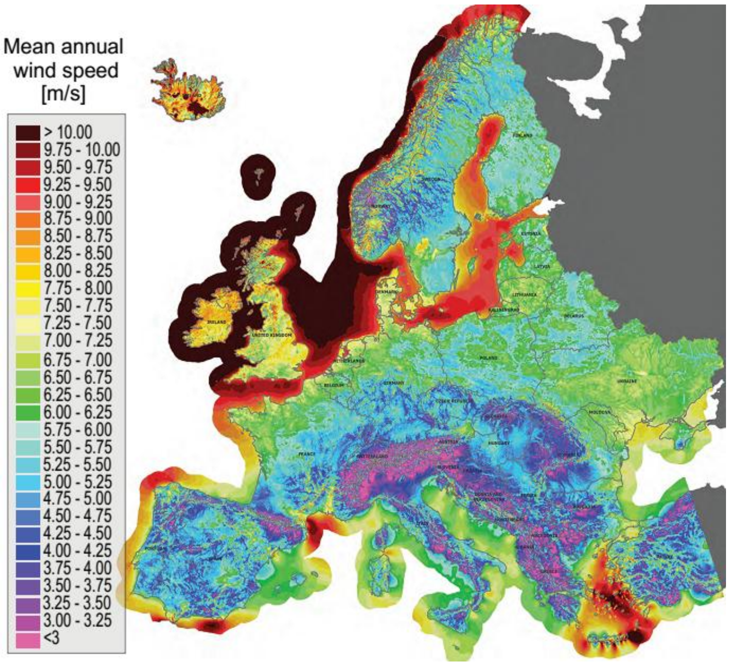
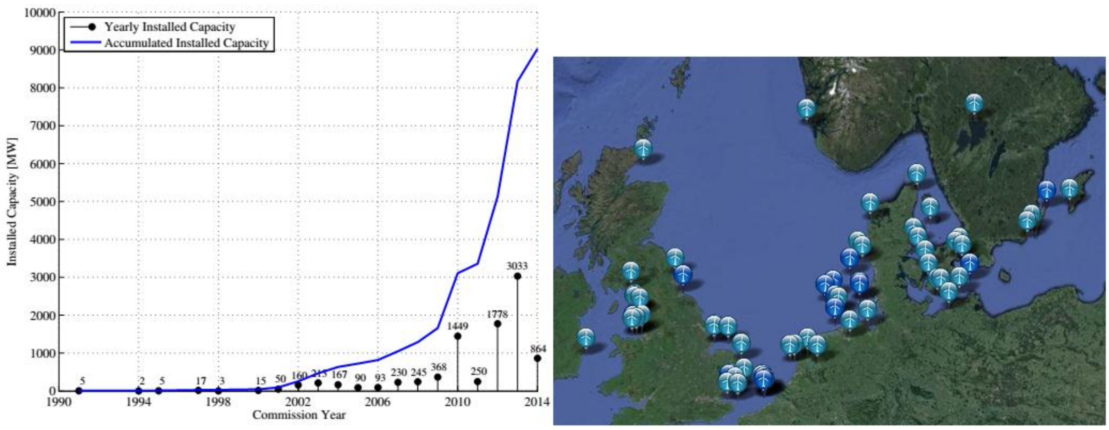


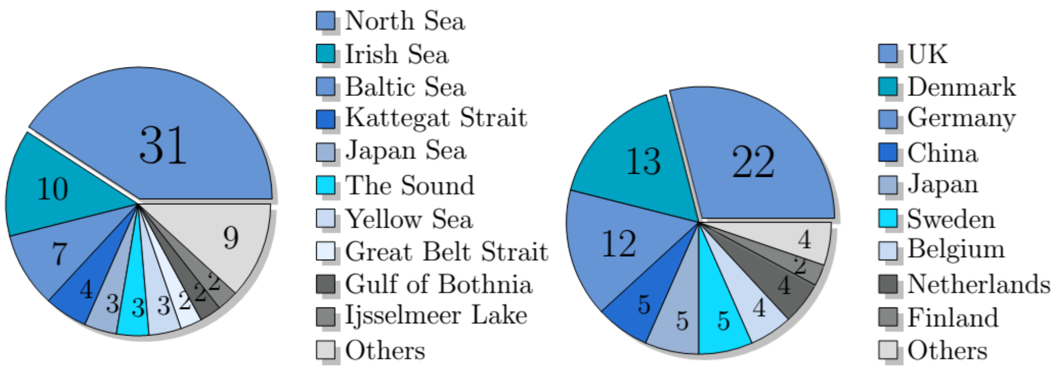
Figure 1: Annual average wind speed at 200 meter resolution and 80 meter hub height [1].



(a) Yearly and accumulated offshore installed capacity for commissioned, and under construction projects.

(b) Commissioned (light blue) and under construction (dark blue) wind farms in the north of Europe.

Figure 2: Offshore installed capacity and location of offshore wind farms in the north of Europe [2,3].



(a) Offshore wind farms locations (b) Offshore wind farms per country

Figure 3: Breakdown of offshore wind farm projects per locations and countries [2].

for the next coming years. Figure 4 shows a prediction for the offshore installed capacity and HVdc interconnections in the North Sea by 2020.

1.2. State-of-the-art for Offshore Wind Farms

Since the first offshore wind project, the Danish Vindeby wind farm, built in 1991, a lot has changed. The installed capacity of the most recent offshore wind farms is incomparable larger to the ones registered in the first steps taken offshore. In Figure 5a it is shown the installed capacity of the offshore wind farms and the yearly average. It is possible to observe that the trend is to increase the installed capacity per project. Moreover, also the distance to shore is increasing as depicted in Figure 5b. Figure 5c shows the total investments costs per offshore project. The industrial trend to build wind farms with higher installed capacities located further from the cost which require higher total investment costs demonstrate that offshore wind is profitable.

In Table 1 a list of 4 offshore wind farms is given. The British offshore wind farm London Array, composed of 175 wind turbines delivered by Siemens (SWT-3.6-120), has an installed capacity of 630 MW and it is the offshore project with the highest installed capacity up to today. Another British offshore wind farm, Greater Gabbard, is the largest project with a total area of 147 km^2 and it is composed by 140 Siemens turbines (model SWT-3.6-107). The German Global Tech 1 offshore farm, currently being installed, is the one built further away from the cost with a mean distance of 126 km. The German Bard Offshore 1 wind farm with a total investment cost rounding 2900 MEUR is the most expensive project up to today. It has an installed capacity of 400 MW, it is situated at a mean distance of circa 95~km from the cost and it makes use of a HVdc transmission system.

Table 1: Offshore Wind Farm Projects List [2,3].

Name	Country	Commission Year	Rated Power [MW]	Number of Turbines	Distance to Shore [km]	Cost [MEUR]	Area [km^2]
London Array 1	United Kingdom	2013	**630**	**175**	20	2000	100
Greater Gabbard	United Kingdom	2012	504	140	26	1615	**147**
Global Tech 1	Germany	2013	400	80	**126**	1600	41
Bard Offshore 1	Germany	2013	400	80	95	**2900**	59

A considerable technological advance has also been made at the turbine level. Figure 6a shows a temporal evolution for the rated power and rotor diameter of the wind turbines. The

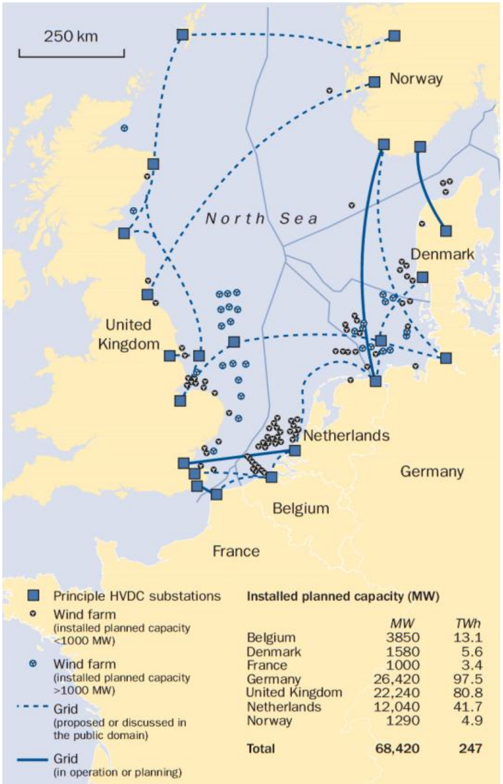


Figure 4: Planned offshore wind farms in the North Sea [4].

first offshore turbines had a 37.5 m rotor diameter, while the most recent have a 126 m rotor diameter. In terms of rated capacity a considerable evolution is also noticeable. The wind turbine REpower 6.15M, made by the manufacturer RWE, is up to today, the turbine in the market with the highest rated power.

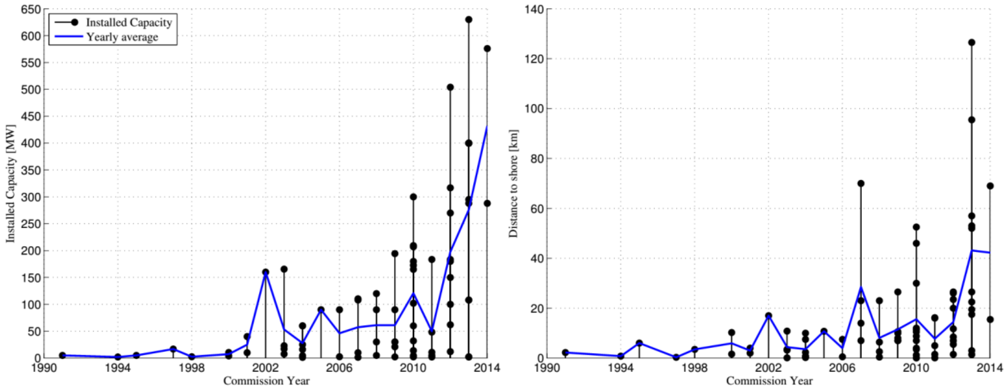
In terms of hub height an increase from 37.5 m to 100 m is found when turbines from the first offshore project are compared to the ones present in the Ems Emden offshore project (see Figure 6b).

The average water depth of offshore wind farm projects has also been increasing along the years. In Figure 7, it is shown the average water depth and respective turbines support structure per offshore farm. In the first projects water depths low than 10 m were registered. In more recent projects, average water depths rounding 45 m were achieved. For instance, in the Alpha Ventus wind farm, 45 m-high jacket foundations were used [2].

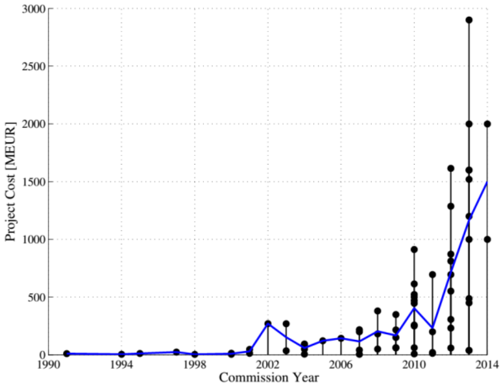
Water depths higher than 50 m required, up to today, floating support structures. This type of structures will be presented later in the report as one the challenges of the deep offshore.

1.2.1. Applied solutions for grid connection

The initial offshore wind farm projects were connected to shore via medium voltage ac (MVac) with a maximum rated voltage level of 33 kV (see Figure 8). In 2002 it was built the first wind farm, the Danish Horns Rev 1 project, making use of high-voltage ac (HVac) as transmission technology with a rated voltage of 150 kV. In 2013 projects making use of high-voltage dc (HVdc) were firstly commissioned.

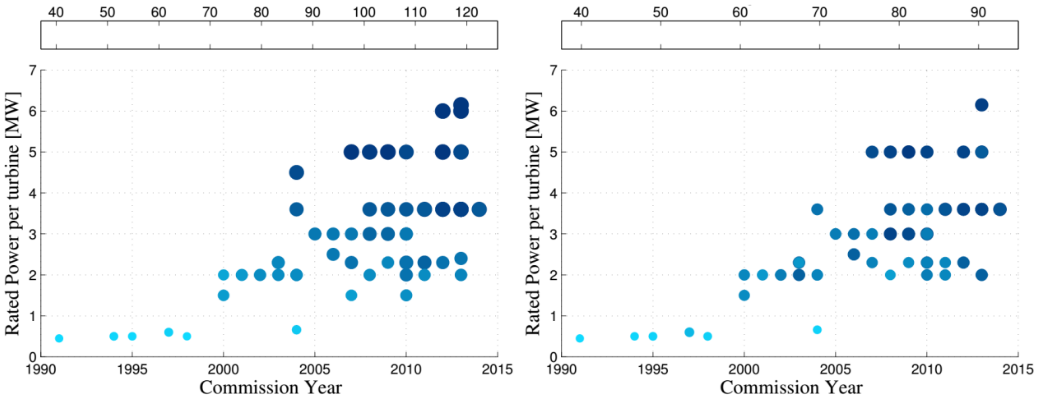


(a) Installed capacity (b) Distance to shore



(c) Total investment cost

Figure 5: Installed capacity, distance to shore and total investment costs per project and yearly average [2,3].



(a) Rotor diameter (b) Hub height

Figure 6: Rotor diameter, hub height and respective rated power for the turbines installed at the commissioned, or under construction, offshore wind farm projects [2].

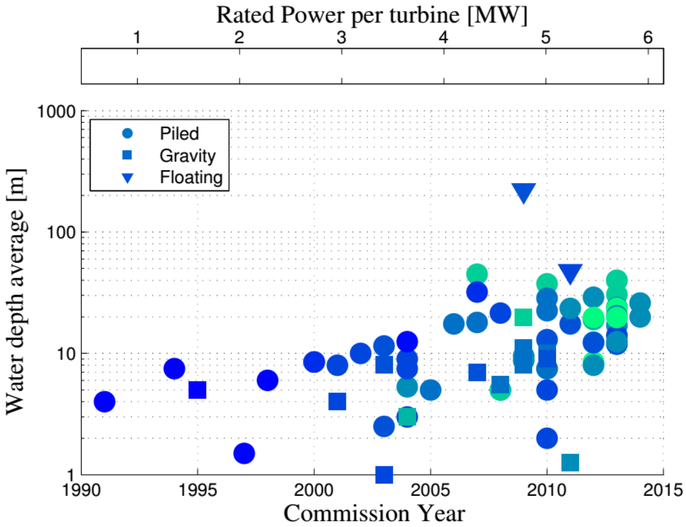


Figure 7: Commission year, type of foundation structure and average water depth per offshore wind farm project [2,3].

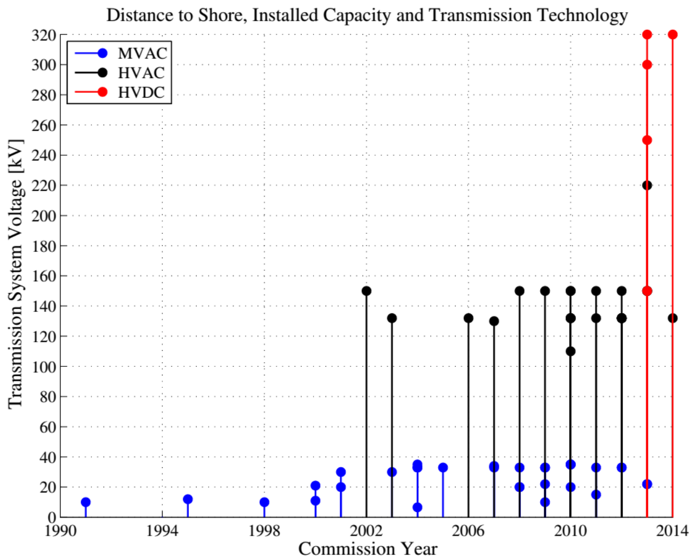


Figure 8: Commission year and transmission system voltage and technology [2,3].

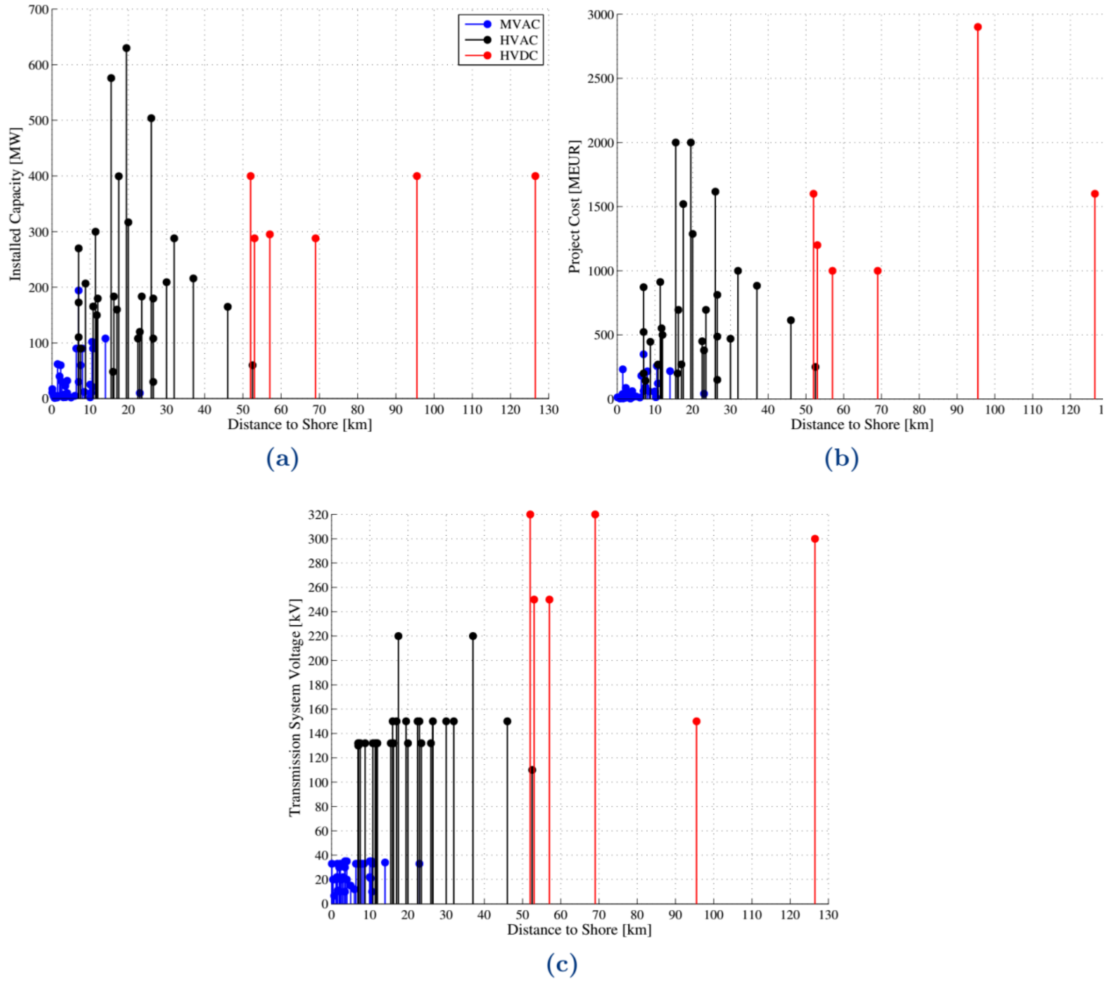


Figure 9: Total cost, installed capacity and transmission technology per offshore project [2,3].

Industry Break-even point

In Figure 9a it is shown that most of the offshore projects make use of MVac or HVac as transmission technology. If the distance to shore is higher than circa 15~km and the project installed capacity is higher than 100 MW, industry has made HVac as the technology of choice. However, for distances higher than around 50~km and installed capacities larger than 100 MW, HVdc was the technology used.

In Figure 9b the costs per offshore project and its distance to shore are shown. Projects that are interconnected via HVdc are the ones that demanded higher initial investment costs. One of the reasons for this phenomenon is the cost of the converter and the extra offshore platform required to house it.

Rated Voltage

The transmission voltage level used in the offshore projects and their respective transmission technology is depicted in Figure 9c. Most of the HVac-based projects have a transmission voltage of 133 kV or 150 kV. The wind farms, Anholt and NorthWind, are the first ones to make use of HVac cables with a rated voltage of 220 kV. Another interesting fact is the lack of system harmonization between the HVdc-base projects. Out of 6 projects, 4 different voltage levels (150, 250, 300 and 320 kV) are used. This choice will bring technical challenges, higher investment costs and additional system losses, if an offshore multi-terminal dc network is pretended.

HVdc technology

Germany is the only country which is building offshore wind projects connected to shore through HVdc technology. Figure 10 shows the location of the transformer substations and converter stations, the transport cable routing and the onshore converter stations. It is important to refer that there are no offshore hubs, i.e. each offshore converter station is directly connected to shore via an independent HVdc cable.

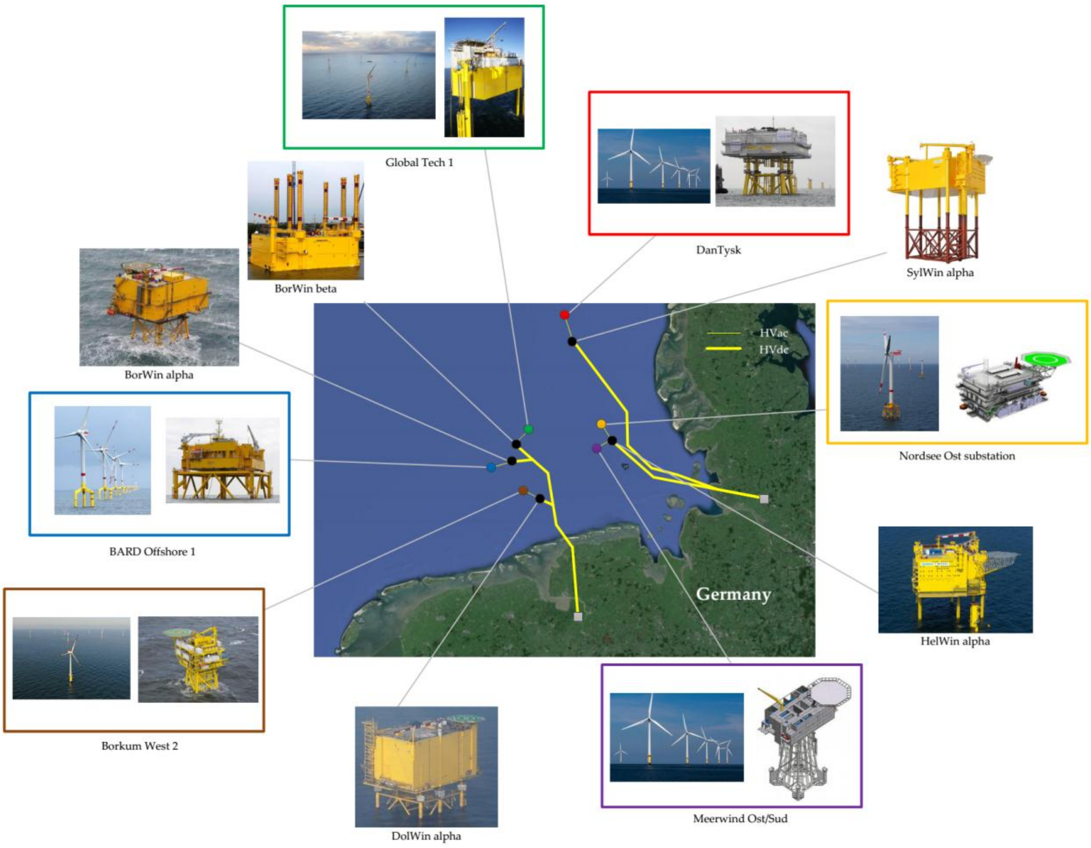


Figure 10: Under construction offshore wind farms interconnected via HVdc transmission system [2,3].

1.2.2. Grid requirements

Grid codes define the requirements for the connection of generation and loads to an electrical network which ensure efficient, safe and economic operation of the transmission and distribution systems. Grid codes specify the mandatory minimum technical requirements that a power plant should fulfill and the additional support required to maintain, such as power balance, power quality and system security. The additional services that a power plant should provide are normally agreed between the transmission system operator and the power plant operator through market mechanisms [7].

The connection codes normally focus on the point of common coupling (PCC). This is very important for wind farm connections, as grid codes demand requirements at the point of connection of the wind farm not at the individual turbine terminals. Nonetheless, grid code requirements have been a major force on wind turbine development; manufactures often claim that grid codes are extra demanding and have influenced development processes [26].

The grid connection requirements differ from country to country and may even differ from region to region. They have many common features but some of the requirements are subtly different, reflecting the characteristics of the individual grids. Next, the most important grid code requirements are presented and discussed.

Frequency operating range

When the ac grid frequency deviates from its nominal value, wind farms are allowed - or required to - disconnect from the system, but only after a time delay. An example is taken from the German transmission system operator (TSO), E.ON Netz: for frequencies above 53.5 Hz and bellow 46.5 Hz, offshore wind farms must be automatically disconnected after 300 ms (see Figure 11). For other frequency values inside this range, they must stay connected for at least the time period indicated in [5].

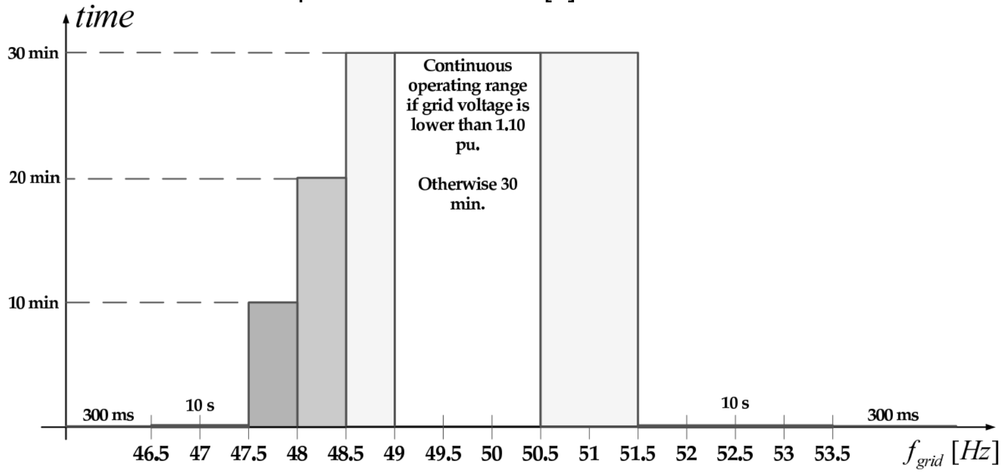


Figure 11: Frequency operating range as according to the German TSO, E.ON Netz [5].

Active power control

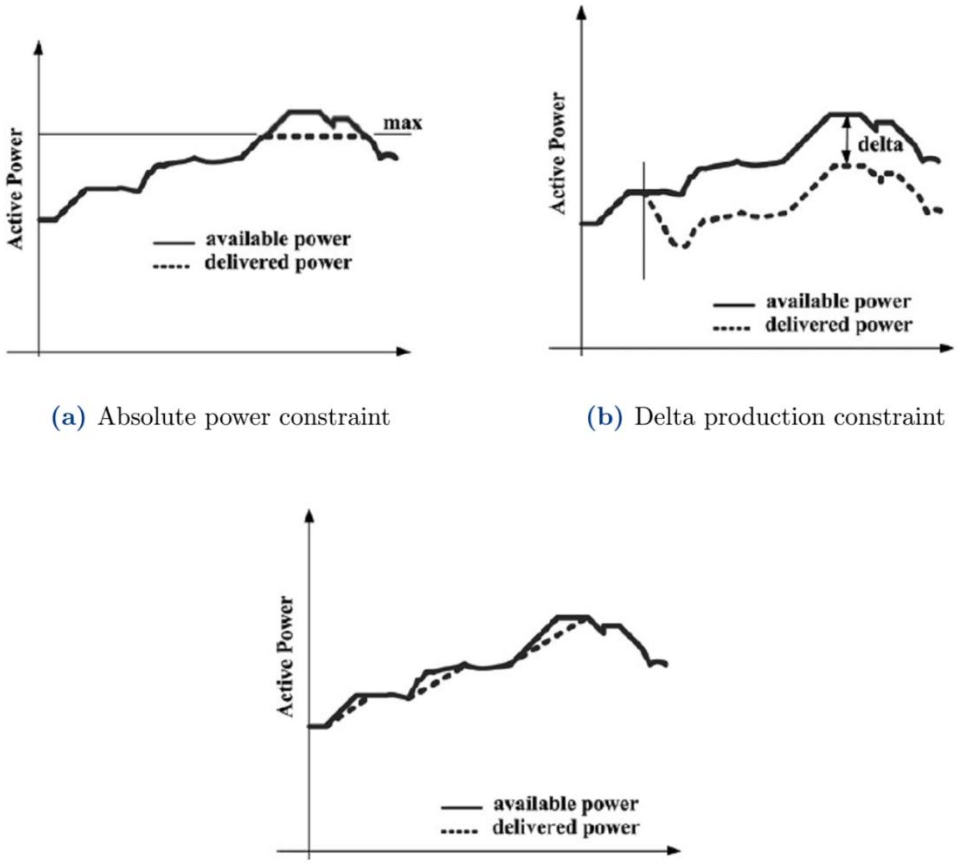
Large wind farms are required to be able to vary their active power output according to set points provided by the TSO. Usually the new set point has to be achieved with a certain minimum rate of change [26]. Additionally, the active power has to be reduced when the system frequency exceeds the normal operating area and the TSO can set a time frame in which the curtailment needs to be achieved:

$$G_p \geq \frac{P_1 - P_0}{t_1 - t_0} \left[\frac{W}{s} \right] \qquad (1)$$

where P_1 is the new power reference, P_0 is the current reference, t_0 is the time in which the transient started, and t_1 is the time the transient finishes.

All grid codes currently impose requirements on the regulation capabilities of the active power of wind farms, taking the form of several different modes of control as illustrated in

Figure 12. Within the constraint of the primarily available active power (i.e. the prevailing wind conditions), output power can be regulated to a specific maximum value (Figure 12a) or to maintain a certain ratio of the available power, such as maintaining a specified reserve, either in MW or as a percentage of the available power (Figure 12b). Additional requirements may include the limitation of the rate of change of the output power (Figure 12c) [6].



(a) Absolute power constraint

(b) Delta production constraint

(c) Power gradient constraint

Figure 12: Constraints over the active power production [6].

Reactive power control

Wind farms are required to help regulate the grid voltage by varying their reactive power output. Depending on the grid code, the specifications for reactive power control might be given as a voltage range, a reactive power range or a power factor (PF) range at the PCC [27]. For instance, the Polish TSO (PSE) defines the PF range as, 0.975 ind≤cosφ≤0.975 cap, whereas the Australian TSO (NEMMCO) defines it as, 0.93 ind≤cosφ≤0.93 cap [26]. Figure 13 shows the operational region as specified in the Great Britain and Ireland grid codes.

In addition to reactive power control during normal operation most TSOs also define rules for reactive current injection during voltage dips and swells. The reactive current amount to be supplied depends on the network voltage. Figure 14(a) shows the reactive current requirement for Spanish wind farms.

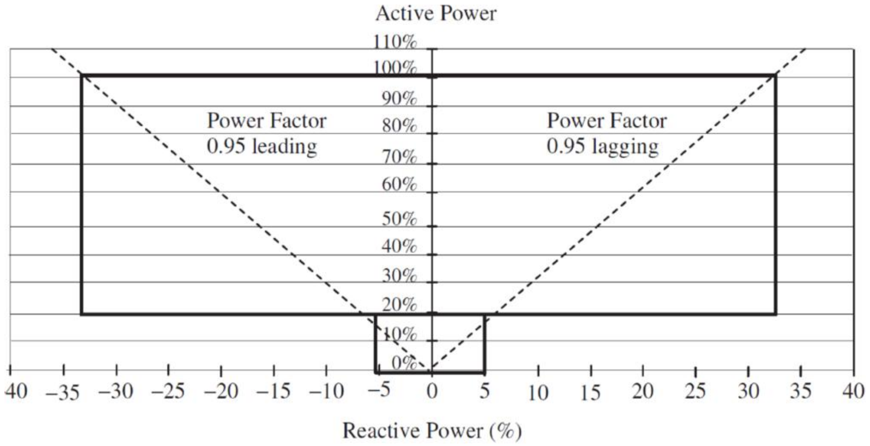


Figure 13: Steady-state operating region for the British and Irish grid codes [7].

Fault-ride through (FRT) requirement

Grid codes invariably demand that large wind farms must withstand voltage dips down to a certain percentage of the nominal voltage and for a specified duration [6]. The FRT requirement specifies the minimum time the wind farms should withstand low voltages in the ac grid without disconnecting. It is usually given at the PCC HV-side level as a function of time [28].

Figure 14(b) shows the FRT requirement from E.ON Netz [5]. The FRT characteristic curve is composed of 4 main areas: in the white part of the diagram wind farms should not disconnect from the network. In the light gray area, short term interruptions (STI) are allowed provided they last for less than 300 ms and in the dark gray area STI are allowed up to 2000 ms. Finally, in the black area, disconnection of the wind turbines is allowed by means of an automatic system. For instance, in the UK, the NGET establishes that for dip durations up to 140~ms, the active power must be restored to 90 % of the pre-fault level within 500 ms after the grid voltage returns being higher than 90 %. In Figure 15 the FRT requirements of several grid codes are depicted.

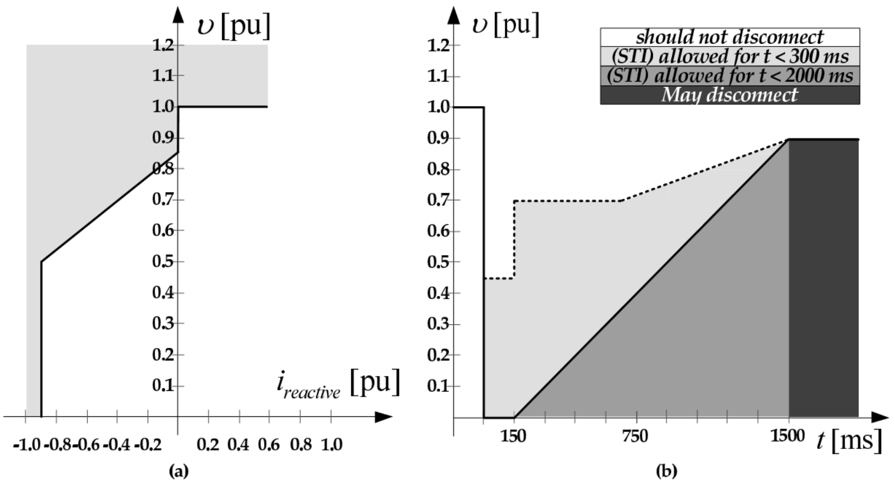


Figure 14: (a) Supply of reactive current during dips for the Spanish grid code and, (b) FRT requirements according to the German grid code [5].

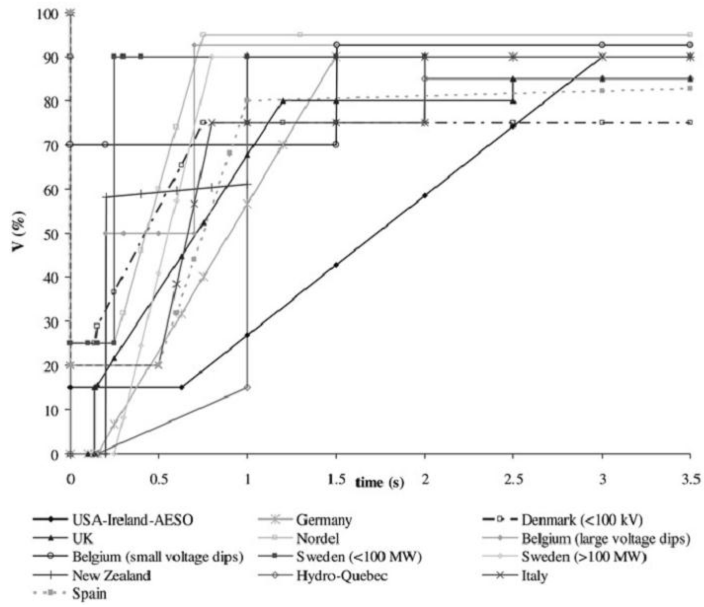


Figure 15: FRT requirements of different grid codes [6].

1.2.3. Challenges

Remarkable technological advances have been experienced in the offshore wind field. As previously said, improvements in the distances to shore, rated capacities of both the wind farms and the turbines, average water depths were achieved during the last 20 years. However the industry faces several significant challenges that must be addressed before offshore can grow to its full potential.

Extreme Conditions

The ocean is a very rough environment due to, among other reasons, storms, strong waves and corrosion from salty water and air. Installing and maintaining wind farms at sea is much more complex than on land, requiring special equipment and favorable weather. Projects in the North Sea have proven that it can be done, but at great costs, which can reach more than double the onshore maintenance costs.

Reliability is one of the most important key issues when it comes to an offshore project. The difficult access - both in terms of wind turbine placement but also weather conditions - may cause undesired extended downtime periods.

The turbine technology is one the key challenges of the market. Initially offshore wind was following the footsteps of onshore wind technology development. The turbines used then may be considered the offshore adapted version of the onshore models. In Europe there are three turbine suppliers that have the lion share of the market: Vestas, Siemens and REpower. BARD and AREVA Multibrid have recently began offshore operation, and many more are expected to enter the market, including Gamesa, Alstom, Clipper, Darwind, General Electric, Mitsubishi, 2-B Energy, Nordex, Doosan and others. This multiplicity of new entrants is likely to result in better commercial terms for developers.

Deep Offshore

As shown in Figure2b the far offshore has not been conquered yet; all the offshore projects are relatively close to the shore. Figure 2a shows that the most valuable wind resources - higher mean annual speeds - may be found far in the offshore. In this way, one of the major present challenges is how to reach the far offshore locations technically and in a viable way to attract investors.

A critical bottleneck to harvest energy at large distances form the cost is the foundation technology. As water depth increases, the use of a steel platform will be limited by economic considerations. In the offshore oil and gas industry, the water depth limit for fixed platforms is about 450 m, but in the offshore wind industry, the limit is likely to be less than 100 m. Floating structures are one of the possibilities to overcome this problem. There are already a few floating test turbines installed offshore. Next two of these projects are presented.

Hywind

The Hywind concept (see Figure 16a), developed by StatoilHydro, is a pilot turbine that was placed in Norwegian waters in 2009. The foundation consists of an 8.3 m diameter, 100 m long submerged cylinder secured to the seabed by three mooring cables. Hywind was towed horizontally to a fjord and partially flooded and righted. Additional ballast was then added and the turbine installed on top.

WindFloat

In 2011, WindFloat was installed in the Portuguese offshore coast. Equipped with a 2 MW Vestas wind turbine, the system started producing energy in 2012. The WindFloat design consists of a semi-submersible floater fitted with patented water entrapment plates at the base of each column (see Figure 16b). The plate improves the motion performance of the system significantly due to damping and entrained water effects. This stability performance allows for the use of existing commercial wind turbine technology. The second phase of the projects compasses the installation of a 27 MW array in the same area.

Safety and Maintenance

Safety and maintenance are very important issues and particularly important in an deep offshore environment where there are more risks and it is more difficult to get help if an accident occurs.

Investment Costs

Offshore wind has the highest costs of any energy generating technology which is currently available on a commercial scale [31]. The high cost of energy generated by offshore wind farms is probably the biggest challenge facing offshore wind and it is imperative to reduce these costs as soon as possible. This reduction can only be achieved through the optimization of every stage of development, manufacture, installation and operation.

Supply Chain

The offshore wind industry faces a series of challenges from the global supply chain, in particular the supply of [31]:

(a) Hywind turbine [29]

(b) Winfloat project [30]

Figure 16: Two floating turbine projects.

- Copper material, for transformers;
- Rare earth minerals, for high permeability permanent magnets;
- Large casting and forging, for bearings, shafts and gearing systems;
- High power semiconductors, for converters;
- High modulus carbon fibre, for wind turbine blades.

The offshore wind industry will have to compete against other industrial sectors for these materials. Such situation may lead to the increase of wind farms capital costs. On the other hand, there are opportunities associated with these shortages, such as the development of alternative technical solutions, e.g. the shortage of copper may lead to the development of aluminum conductors for submarine cables.

There are very few suitable harbors with large deep water quays and areas required for wind turbines assembling. The supply of suitable vessels capable of installing offshore wind farms is also a matter of concern. The market has answered by building new wind turbine installation vessels. However, there is still a shortage of vessels capable of installing array and export offshore cables. The offshore oil and gas industry operates vessels capable of installing these cables. However the global offshore oil and gas market is buoyant, therefore these vessels may not be available to install wind farm cables.

There is insufficient capacity to manufacture the amount of submarine cables required for the planned offshore wind farms. Cable manufacturers have recognized the market opportunity and are building new quayside factories. Nonetheless, several cable manufacturers have reported current backlogs of two years or more, which indicates that current supply is only just keeping up with demand.

There is a similar shortage in the capacity to build offshore wind turbines. To achieve the EU 2020 targets, it is likely that between three and five turbines will have to be installed per day, or between approximately 1000 and 1800 per year. These quantities are for the offshore market and exclude the demand for onshore turbines. Currently there is a significant shortfall in the capacity to build offshore turbines.

A large offshore wind industry will require engineers and technicians to install and operate them. There is a concern over the availability of suitably qualified people.

1.3. Scope of the Report

When considering to combine offshore wind farms with interconnectors, technology of the electrical infrastructure is a main factor in the costs as well as in the expected performance and reliability. In order to realize such innovative infrastructure the availability of the technology in terms of technical maturity and supply chain issues is also important.

For the intended combination several different grid topologies are possible, each with many different possible technical implementations. Therefore a systematic, comprehensive overview of the available technologies is needed. The focus of this review is on high-voltage offshore transmission systems and electrical systems and characteristics of offshore wind farms. Particular issues that are addressed are the combination of high-voltage ac (HVac) and high-voltage dc (HVdc) technologies, the interfacing between wind farms and offshore grids and the required infrastructure, i.e. substations, and the control and protection of offshore grids.

Within the feasibility stage of the project “Synergies at Sea”, sub-project “Interconnector” this technology review of wind farm and offshore grid electrical systems should provide a basis for:

- Providing insight in the state-of-the-art technologies and their main characteristics, mainly for the technical work stream but also for the others;
- Defining technical requirements and selecting proper technologies for the different grid layouts, i.e. defining the technical scenarios;
- Defining evaluation criteria for the preliminary feasibility assessment;

This review also provides input to the technical R\&D work stream for:

- Identifying key objectives and parameters to optimize the design;
- Making an inventory and identifying the need for dedicated power-electronic converters to enable certain offshore grid solutions.

Part II first presents the main components of the electrical system, both High Voltage AC (HVAC) and High Voltage DC (HVDC), each with their characteristics and typical applications. Also the fundamentals of wind turbines and farms collection grids are presented, as these determine the behavior of the wind farms as part of a larger grid, for instance power variability and control capabilities, e.g. voltage support. Part III presents the selected basic scenarios and discusses the different technical implementations.

2. Wind Farm Concepts

In this section, the components present in a modern wind turbine are presented. Thereafter, the most common topologies, with regard to the generator and converter - if present - types are introduced and explained. In the last part, an overview of the internal electrical system of an offshore wind farm is given.

2.1. Overview of wind turbine topologies

Figure 17 illustrates the components that are usually found in the nacelle of a modern wind turbine.

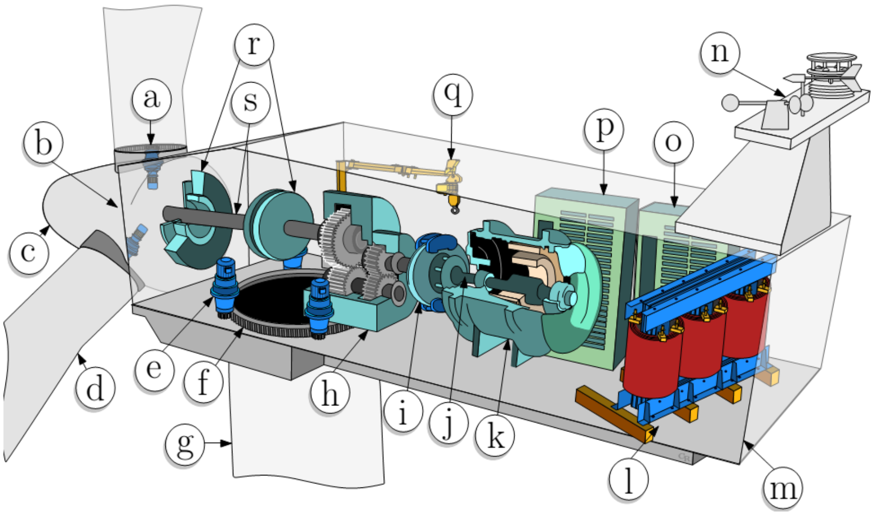


Figure 17: Typical wind turbine nacelle components: (a) pitch drive, (b) rotor hub, (c) spinner, (d) blade, (e) yaw gear, (f) yaw ring, (g) tower, (h) gearbox, (i) break disc, (j) high-speed coupling, (k) generator, (l) transformer, (m) canopy, (n) meteorological sensors, (o) power converters, (p) nacelle control panel, (q) service crane, (r) main bearing, (s) main shaft.

The pitch drive system (indicated as (a) in Figure 17) is responsible to readjust the wind turbine blades in order to allow the turbine rotor to achieve optimal rotational speed. Moreover, if the rated wind speed is exceeded the power has to be limited. Active stalling the turbine blades through the pitch system is one possibility. Stalling works by increasing the angle at which the relative wind strikes the blades (angle of attack), and it reduces the induced drag. A fully stalled turbine blade, when stopped, has the flat side of the blade facing directly into the wind.

The wind direction is not stationary, hence, in order to maintain the energy production at its optimum, the turbine should face the main wind direction at all times. This feature is performed via the yaw system, composed by the yaw gear and the yaw ring (components (e) and (f), respectively).

The gearbox (component (h)) is responsible for transforming the slow motion of the turbine rotor to fast revolutions per minute required by the generator rotor. It is a very important component in a wind turbine and it is a component whose reliability has been an issue in the past.

The meteorological stage (indicated as (n) in Figure 17) measures the wind speed and direction and transmits these information to the nacelle controller in order to keep the turbine facing the wind at all times. In emergency situations or when the wind speed is too high a brake is used to stop the turbine rotor. All these components are not directly involved in the power conversion, however they play a very important role to ensure the proper, efficient, and reliable operation of the system [32].

The generator (component (k)) has the task of transforming the rotor kinetic motion into electrical energy. It is one of the most important components of a wind turbine and several technological options are available in the market (see Figure 18a). The presence of power converter (component (o)) in the wind turbine is not mandatory, but more recently their presence has been witnessed. As it is possible to observe in Figure 18b, the first offshore wind projects where composed by wind turbines that did not make use of any power converters. Moreover, asynchronous generators were employed in these offshore projects.

In a second technological step, doubly-fed induction generators (DFIGs) were being installed, hence rotor power converters started to be employed. Wind turbines equipped with DFIGs are, up to date, present in circa 42 % offshore projects which are built or being installed [2]. Moreover, approximately 31 % of the offshore installed power makes use DFIGs.

Nowadays, permanent magnet synchronous generator (PMSG) based-systems are starting to attain turbine manufactures attention. Circa 15 % of the installed offshore projects, and 11 % of the offshore installed power, make use of PMSGs systems. Two offshore projects, Global Tech 1 [33] and Borkum West 2 [34], each with 80 5-MW-AREVA turbines, with a 116 m rotor radius, are currently under construction. The turbines will be equipped with PMSGs and full-rated converters. Moreover, a considerable percentage of the large WTs (5-10 MW range) being developed make use of PMSG technology [35]. A description of the most common wind turbine concepts are given next.

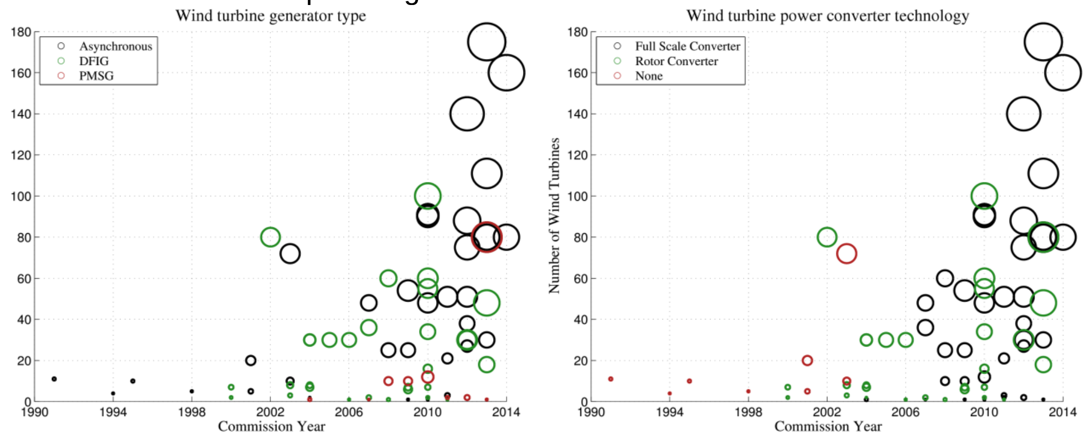


Figure 18: Generator type and power converter technology for the turbines installed at the commissioned, or under construction, offshore wind farm projects [2,3]. The circles diameter is related to the projects installed capacity.

2.1.1. Fixed-speed Wind Turbine

Fixed-speed wind turbines are electrically simple devices consisting of an aerodynamic rotor driving a low-speed shaft, a gearbox, a high-speed shaft and an induction/asynchronous generator. Figure 19 illustrates the configuration of a fixed-speed wind turbine. It consists of a squirrel-cage induction generator coupled to the power system through a transformer.

The generator operating slip changes slightly as the operating power level changes and the rotational speed is therefore not entirely constant. However, since the operating slip variation is generally less than 1\%, this type of wind generation is normally referred to as fixed speed. Squirrel-cage induction machines consume reactive power, thus capacitors are installed to allow power factor correction. The function of the soft-starter unit is to build up the magnetic flux slowly and so minimize transient currents during energization of the generator.

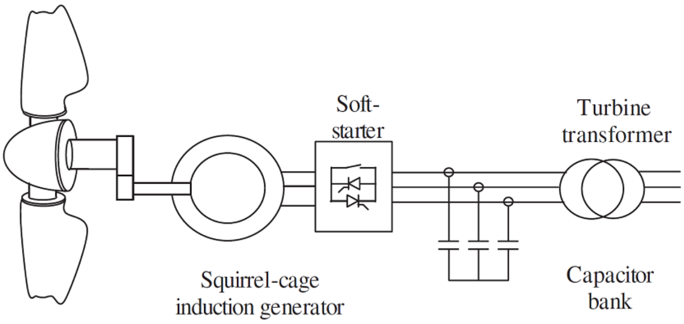


Figure 19: Schematic of a fixed-speed wind turbine [7].

2.1.2. Variable-speed Wind Turbines

In the most recent wind turbines the technology has switched from fixed speed to variable speed. The drivers behind these developments are mainly the ability to comply with demanding grid code connection requirements and the reduction in mechanical loads achieved with variable-speed operation. Next, the most common variable-speed wind turbine configurations are presented and described.

Doubly-Fed Induction Generator (DFIG) Wind Turbine

A typical configuration of a DFIG wind turbine is shown in Figure 20. It uses a wound-rotor induction generator with slip rings to take current into or out of the rotor winding. Its variable-speed operation is obtained by injecting a controllable voltage into the rotor at slip frequency. The rotor winding is fed through a variable-frequency power converter, typically based on two AC/DC IGBT-based voltage source converters (VSCs), interconnected by a DC bus. The power converter decouples the network electrical frequency from the rotor mechanical frequency, enabling variable-speed operation of the wind turbine. The generator and converters are protected by voltage limits and an over-current ‘crowbar’.

A DFIG system can deliver power to the grid through the stator and rotor. Depending on the rotational speed of the generator the rotor can also absorb power. If the generator operates above synchronous speed, power will be delivered from the rotor through the converters to the network. On the other hand, if the generator operates below synchronous speed, then the rotor will absorb power from the network through the VSCs.

Fully Rated Converter (FRC) Wind Turbine

Figure 21 shows the typical configuration of a fully rated converter wind turbine. Depending on the generator used, induction, wound-rotor synchronous or permanent magnet synchronous, the turbine may or may not include a gearbox.

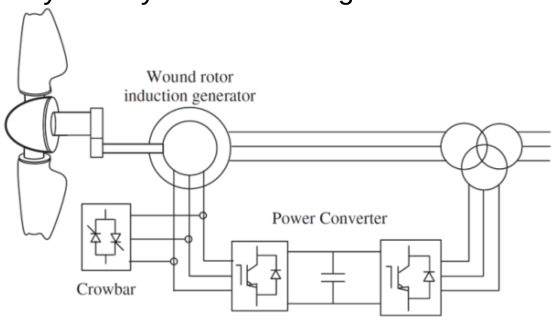


Figure 20: Typical configuration of a DFIG wind turbine [7].

Since all the power from the turbine flows through the power converters, the dynamic operation of the electrical generator is effectively isolated from the power grid. The electrical frequency of the generator may vary as the wind speed changes, while the grid frequency remains unchanged, thus allowing variable-speed operation of the wind turbine. This turbine concept with fully-rated VSCs in a back-to-back configuration is the most used in the recent offshore projects. The more demanding grid codes may be one the main reason behind this industrial trend.

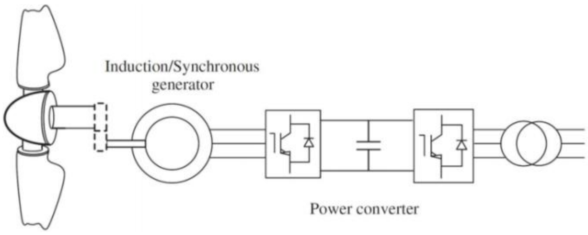


Figure 21: Typical configuration of a fully rated converter-connected wind turbine [7].

2.2. Wind Farm Internal Electrical System

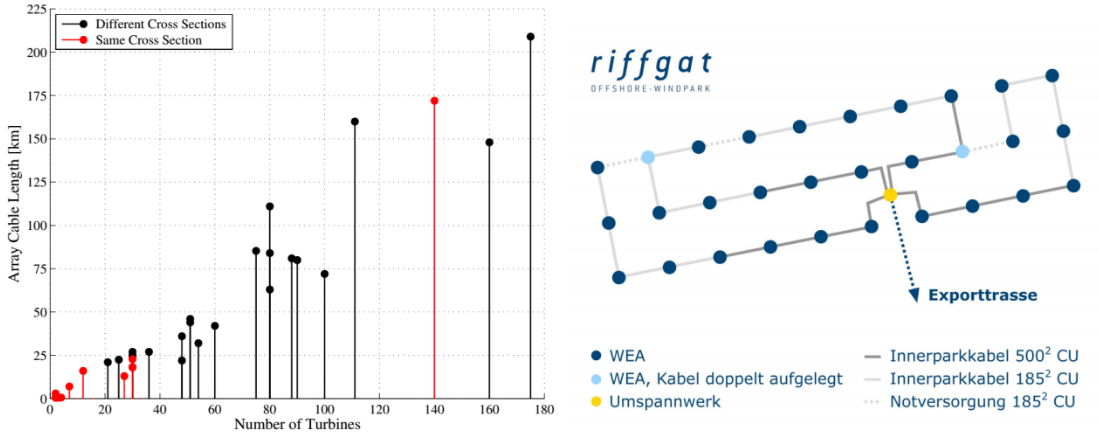
The inter-turbine array cables are responsible for interconnecting the turbines between each other and the substation. The cables between turbines are relatively short in length (typically in the range 500 m to 950 m), while the cables between the offshore substation and the turbine arrays could be longer and possibly up to 3 km.

The inter-turbine array cables are typically 33 kV, 3-core copper conductors with insulation/conductor screening and steel wire armored. The insulation may be either dry type XLPE, wet type XLPE or a combination of both. Usually the cables contain optical fibres embedded between the cores. The ranges of indicative cable conductor sizes and overall diameters that may be used are shown in Figure 22.

Details	33kV Cable Type				
	95 mm²	240 mm²	400 mm²	630 mm²	800 mm²
Overall Diameter (mm)	89	104	127	143	153
Weight (kg/m)	12.2	18.6	38	49	59
MVA (approx)	18	29	36	44	48

Figure 22: Typical cable characteristics for XLPE 33 kV cables [8].

In Figure 23a it is shown the number of turbines and respective total array cable length for the commissioned, or under construction, offshore wind projects. It can be seen that, with the exception of one project, the British Greater Gabbard wind farm, if the offshore projects are composed by more than 30 turbines, or if the total array cable length is higher than 25 km, array cables with different cross sections were used. This strategy allows for costs reduction since cables with lower rated power, hence lower cross sections, were installed. In this way, only the cables that interconnect the last wind turbines to the substation have the rated power level able to carry the power of the entire turbine array. Figure 23 shows the collection system layout of the German offshore wind farm Riffgat where three different cable cross sections were installed.



(a) Collection systems total length (b) Riffgat collection system

Figure 23: Collection system length per offshore wind farm and collection system cable routing for the German wind farm Riffgat [2].

So far the most common, and also the highest, voltage level used in the collection system is 33 kV [2]. In a study carried out by the Carbon Trust, it was concluded that if a 66 kV collection system would be used rather than a 33 kV one, the costs would increase by 12%, while the transmittable power would be doubled (see Figure 24) [9].

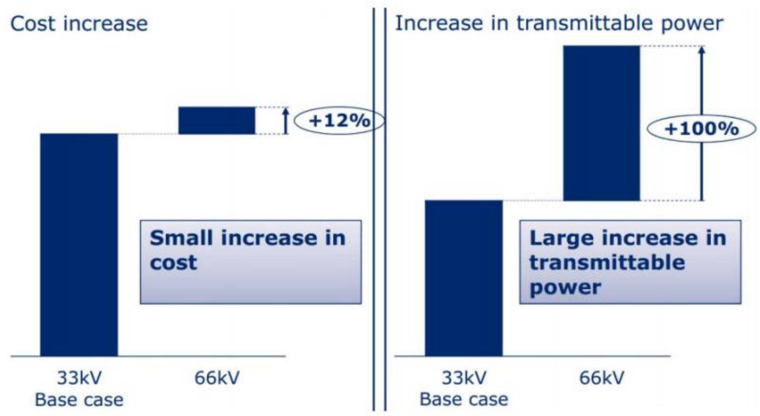


Figure 24: Cost and transmittable power between 33 and 66 kV collection systems [9].

2.3. Transmission technologies

2.3.1. Comparison between HVAC (fixed frequency) and HVDC

High-voltage ac electricity is preferred for transmission purposes mainly because, since it is easier to achieve higher voltages by means of a transformer, it has lower transmission losses. Additionally, generating electricity via three-phase synchronous generators is easier, cheaper and more efficient than using HVDC converters.

However, sometimes it is not possible to use HVAC transmission technology -- e.g. when networks are asynchronous, i.e. have different frequencies, or when long underground or submarine cables are involved.

A list of reasons is given next on why nowadays dc systems are preferred over ac systems for applications such as microgrids, electronic power distribution systems and HVDC grids for integration of renewable energy.

Greater power per conductor

Consider an HVac and an HVdc system with equal current ratings, the same number of conductors, and insulation length in each conductor. The ratio between the power transmitted by the HVdc system, P_{dc}, and the power transmitted by the HVac system, P_{ac}, is given by:

$$\frac{P_{dc}}{P_{ac}} = k\frac{k_1}{k_2} \quad (2)$$

Typical values of k are between 1-$\sqrt{2}$ for overhead lines and 2-3 for underground cables; whereas typical values for k_1 and k_2 are 2.5-3.0 and 1.7-2.0, respectively.

Substituting in (2) typical values for the insulation constants (k, k_1 and k_2) shows that an overhead HVdc line can take 1.5 to 2.1 times more power than an HVac overhead line and an underground HVdc line can take 2.9 to 3.8 times more power than an underground HVac equivalent [36]. This means HVdc systems carry more power per conductor used.

Higher voltages possible

The relationship in (2) shows more power can be delivered using HVdc systems because it achieves higher voltages than HVac systems. The highest alternating voltage achieved commercially has been 1200 kV on a line connecting Russia and Kazakhstan. The line went in operation in 1988 and was dismantled in 1996; whereas since 2010 HVdc voltages of up to 1600 kV (± 800 kV) were already possible, such as in the Xiangjiaba-Shanghai HVdc transmission line in China [37].

Simpler line construction

Usually HVdc transmission lines only comprises 2 cables, whereas HVac lines will require a third one. Moreover, due to steady-state and transient stability limits of ac lines, to transmit the same power more ac circuits are needed [36]. The result is that HVdc needs lesser insulators, have cheaper and smaller towers, and a narrower right-of-way (ROW).

Figure 25 shows that for the transmission of 2000 MW, using a ± 500 kV HVdc line the ROW is circa 50 m. For an HVac line, due to stability limits, the ROW is doubled with regard to that of an HVdc line, since an additional three-phase circuit is needed to transmit the same 2000 MW [38]. Therefore, building an HVdc line is usually 30% cheaper than for its HVac equivalent [39].

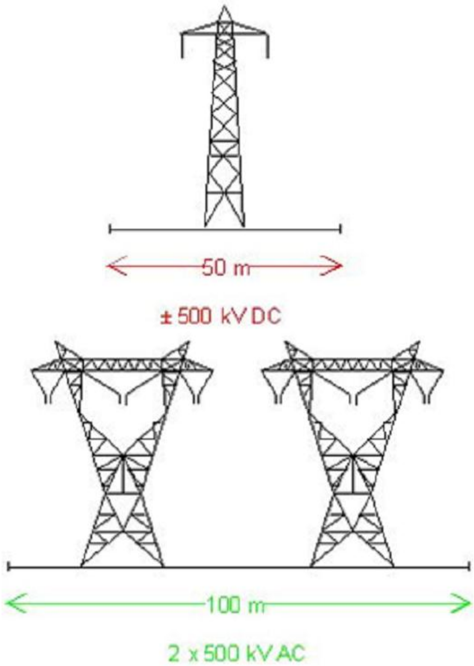


Figure 25: ROW Comparison.

Transmission distance is not limited by stability

Due to voltage stability reasons, the power flow between two nodes connected via an HVac transmission line is limited [40]. Fig. 26 shows a single phase representation of a two-node HVac network. The left-hand side node is the sending node where voltage is controlled at 1 pu, whereas the right-hand side node is the receiving node.

The voltage at the receiving node, v, is given by a bi-quadratic equation:

$$v^4 + \left[2(rp + xq) - e^2\right]v^2 + \left(r^2 + x^2\right)\left(p^2 + q^2\right) = 0 \quad (3)$$

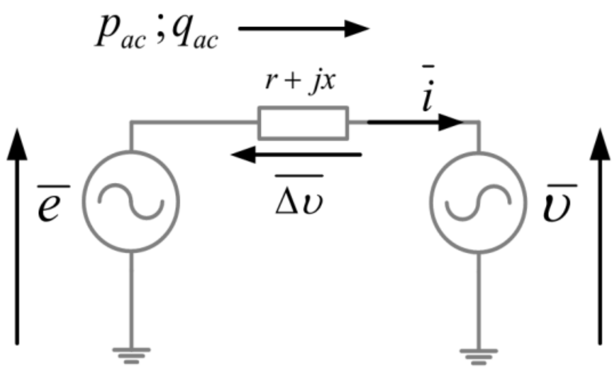


Figure 26: Single phase representation and phasor diagram of a two-node HVac network.

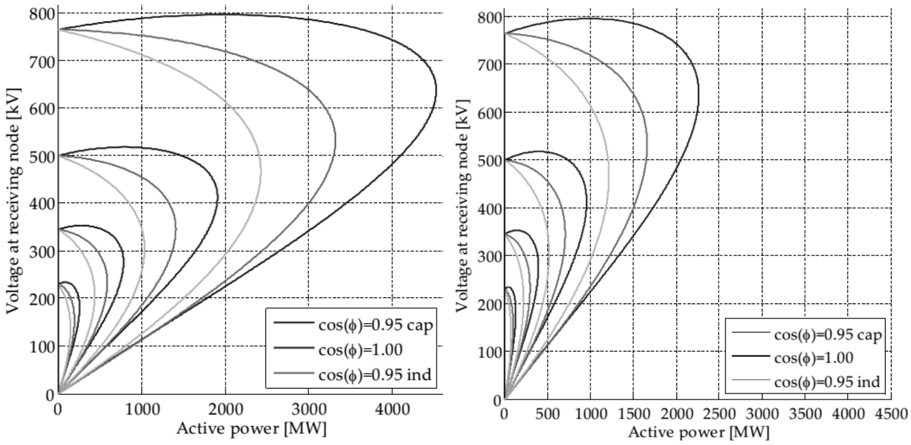
where,
v is the voltage at the receiving node [V];
e is the voltage at the sending node [V];
r is the transmission line resistance [Ω/km];
x is the transmission line inductance [H/km];
p is the line active power [W] and
q is the line reactive power [VA].

If the power factor at the receiving node is known, then substituting q = p tanφ into (3) and rearranging with respect to p, yields:

$$\left[(r^2+x^2)\sec^2\phi\right]p^2+\left[2v^2(r+x\tan\phi)\right]p+(v^4-(ev)^2)=0 \qquad (4)$$

Figure 27 shows a series of curves - known as nose curves - obtained by solving (4) for the receiving node voltage as a function of the transmitted active power between the two nodes and different power factors (cos φ).

The curves shown in Figure 27 have a point where the transmitted active power is maximum, corresponding to a maximum load angle. The maximum power is transmitted when the inflexion of p = f(v) changes, i.e. $\partial p/\partial v=0$, while all the other parameters - e,x,r,φ - are held constant.



(a) Transmission Distance = 250 km (b) Transmission Distance = 500 km

Figure 27: Maximum transmittable power using HVac as a function of the line voltage and power factor.

Figure 28 shows the maximum transmittable power of typical HVac transmission lines as a function of the line surge impedance loading (SIL) and transmission distance, considering the receiving node to have unity power factor [13]. The line parameters used to perform the calculations are given in Table 2.

The HVac line surge impedance, Z_s, is obtained as: $Z_s=\sqrt{X_l X_c}=\sqrt{l/c}$, whereas the surge impedance loading is calculated as $SIL=E_L^2/Z_s$, where E_L is the rated voltage of the transmission line.

With HVac transmission, to transfer power above the line SIL, the transmission distance has to be kept short and the power factor has to be kept as capacitive as possible, for instance by adding shunt capacitors along the line. To transmit power below the line SIL, shunt inductances might be needed. In long-distant overhead HVac lines the stability limits are more critical, whereas in shorter transmission lines - and also in underground and submarine cables - the thermal limits (ampacity) tend to limit the power transfer [13].

Table 2: Typical parameters of HVac transmission lines [13].

Voltage [kV]	r [Ω/km]	X_l [Ω/km]	X_c [kΩ-km]	Z_s [Ω]	SIL [MW]
69	0.1740	0.441	267.1	343.1	14
115	0.0734	0.449	271.9	349.6	38
230	0.0622	0.483	293.3	376.0	141
345	0.0373	0.367	222.0	285.3	417
500	0.0174	0.337	204.3	262.6	952
765	0.0118	0.341	206.0	264.8	2210

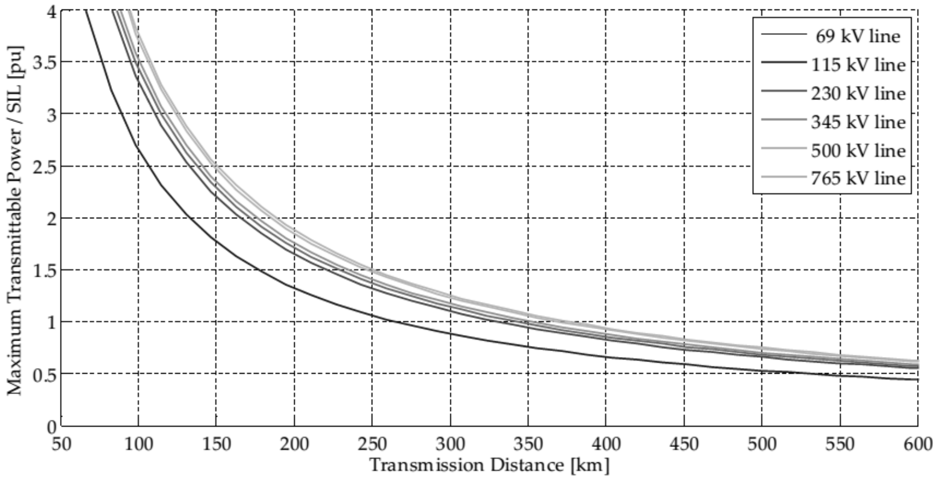


Figure 28: Maximum transmittable power as a function of the line SIL and transmission voltage for an HVac line where the receiving end has a unity power factor (cosφ=1).

Higher efficiency

The initial motivation for the development of HVdc systems was the higher efficiency, as electricity transmission in dc does not suffer from the skin and proximity effects. Both effects contribute to a non-uniform current distribution in conductors carrying ac, where most of the current is found in the conductors outer layers. The result is an increased effective resistance when electricity is transported in ac rather than in dc, resulting in higher transmission losses. Figure 29 shows the skin effect on Partridge and Drake ACSR conductors for HVac systems.

Additionally, dc lines do not require reactive power compensation since the line power factor is always unity, which also translates in lower losses if dc transmission is used.

Each conductor can be an independent circuit

If there is no environmental restriction to the use of ground as a return path, each HVdc conductor can be used as an independent circuit in case of a fault, which is not possible with HVac transmission systems [36,40].

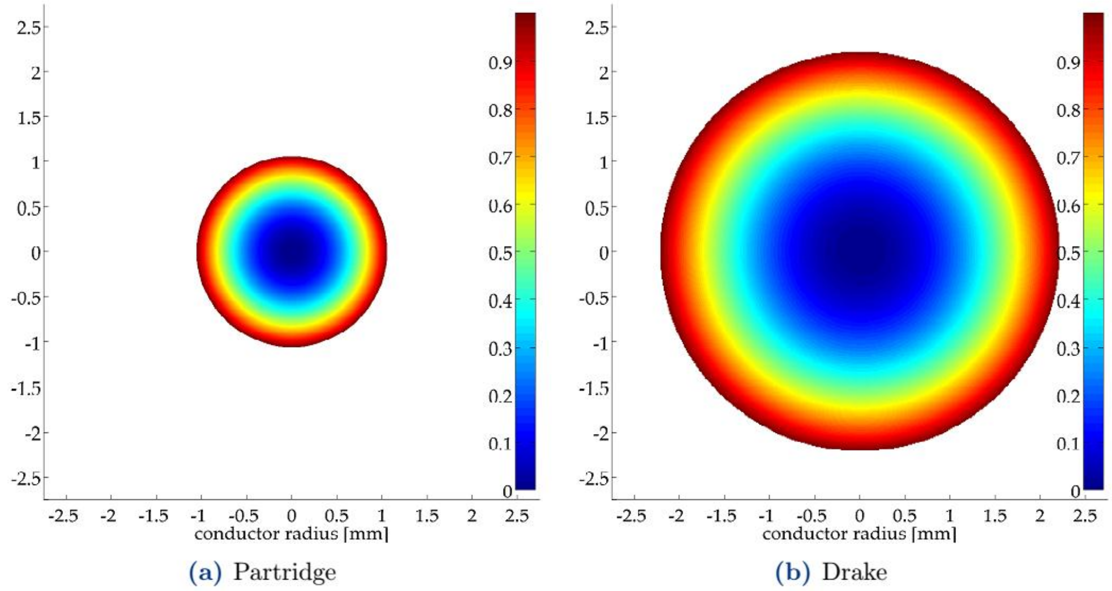


Figure 29: Skin effect on one conductor of high-voltage ACSR cables.

Synchronous operation is not required

One of the main reasons to use HVdc systems is to interconnect different asynchronous ac systems, which can have the same or different frequencies, as is the case of the HVdc links between, for example: Brazil and Argentina (Garabi links), Brazil and Paraguay (Acaray), Russia and Finland (Vyborg), the USA and Mexico (Sharyland), France and the UK (Cross channel), and the Netherlands and Norway (NorNed) [41,42]. Figure 31 shows the six European synchronous zones. Figure 30 shows some of the HVdc transmission systems in Japan, famous for having both 50 and 60 Hz ac systems [43].

Additionally, as dc system do not required a synchronous operation, it can free generators in wind, hydro and natural gas power plants to operate at their maximum efficiency speed curves, which may differ from the main grid frequency.

Does not contribute to short-circuit current of the ac system

During faults in one of the ac systems connected to an HVdc transmission system, the current from the HVdc link can be controlled to zero or to a pre-established value. Hence, HVdc systems do not contribute to the short-circuit current during an ac system fault [36,44].

Less problems with resonances

In HVac systems there are unexpected voltage rises due to resonances between the transmission line impedance, transformers and, capacitors and reactor banks used to compensate the ac line power factor. There are four main categories of resonances in HVac systems: near resonance, harmonic resonance, ferroresonance and subsynchronous resonance [45]. In HVdc systems there are less resonance related voltage surges as cables used for HVdc transmission have resonance peaks in high-frequencies (over 10 kHz) and the harmonic content on the dc side can be easily mitigated via low-pass filters.

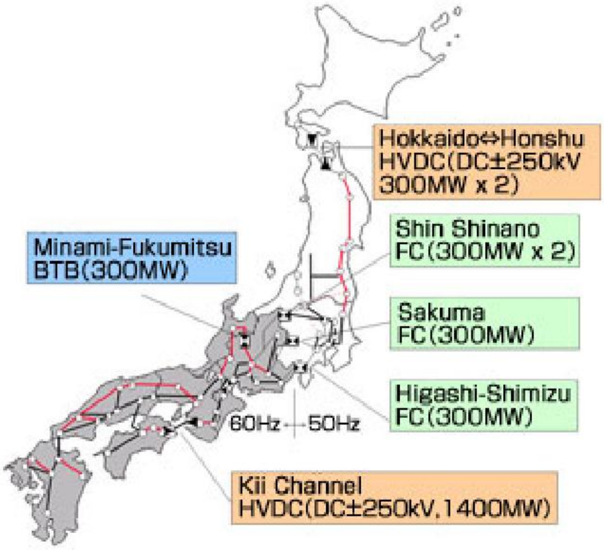


Figure 30: HVdc projects in Japan.

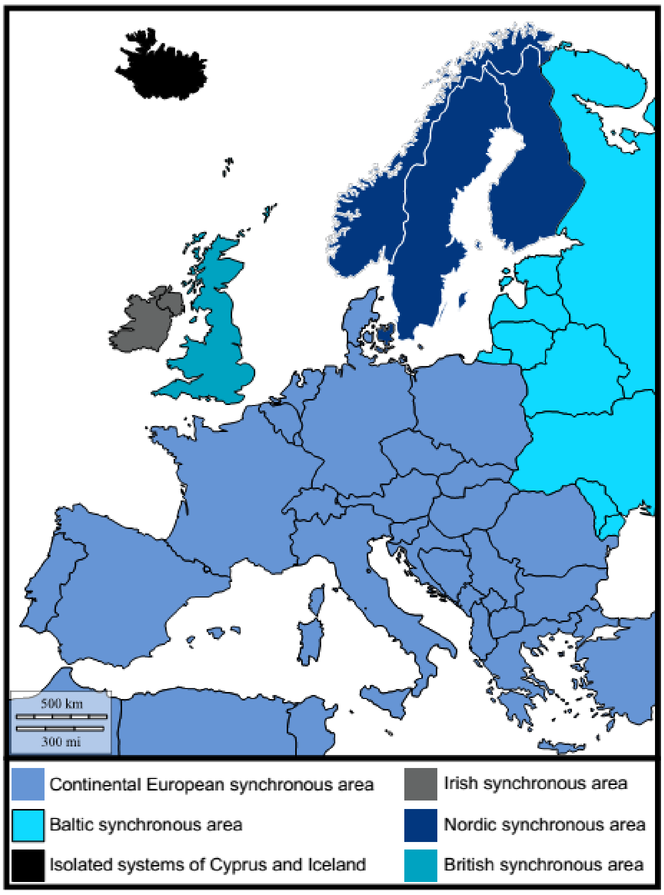


Figure 31: European synchronous zones [10,11].

High controllability

In HVdc systems, the used converter technologies result in higher controllability. Namely, voltage-source converters (VSCs) utilize insulated gate bipolar transistors (IGBT), which are controlled with pulse width modulation (PWM) controllers. The use of fully controllable switches allows to independently control the converter active and reactive power, as well as

DC voltage and AC voltage; the latter in case of connection to a weak AC grid. In this way, the power quality is enhanced and the realization of multi-terminal HVDC networks is theoretically easier, as low coordination among the VSCs is required.

Cables - HVAC vs. HVDC

The selection of which transmission technology to use - HVac or HVdc - depends on the technical aspects of each project. For the connection of an offshore wind farm, it is usually based on efficiency and economic viability calculations, where the two most important parameters to consider are the offshore wind farm distance to shore and its installed capacity.

To cross long distances by means of submarine cables the HVdc solution starts to be preferable in comparison with traditional HVac lines, since the latter has higher losses (due to skin effect and leakage capacitive current) and will demand additional equipment to provide reactive power compensation [46]. Hence, selecting HVac transmission for the connection of offshore wind farms has the following disadvantages [47]:

- Long submarine ac cables produce large amounts of capacitive reactive power;
- There is need to provide reactive power compensation (from STATCOMs or SVCs);
- Transmission capability decreases sharply as a function of distance given the reactive power production and high dielectric losses through the cable. Nevertheless, in comparison with HVdc systems, HVac transmission systems have a wider dissemination since they are more straightforward to install and present a lower footprint when installed offshore [36]. Hitherto, the majority of the operational offshore wind farms in Europe have been connected through an HVac transmission system to shore. The main reasons for choosing this technology are given the fact that currently only a few offshore wind farms have power ratings above 200 MW and almost all of them are located within less than 30 km to shore [48].

Hence, in addition to the load current, ac cables must carry the reactive current generated by the cable distributed capacitance, which impairs the transmittable active power through the cable. The total active power which can be transmitted using an ac cable can be calculated as:

$$P_{ac} = \sqrt{S^2 - Q^2} \quad (5)$$

where,

P_{ac} is the ac cable transmittable active power [W];

S is the ac cable rated apparent power [VA] and

Q is the ac cable generated reactive power [VAr].

Assuming a constant voltage and current throughout the ac cable, its total generated reactive power per is:

$$Q = Q_c - Q_l = 3\omega c d E_p^2 - 3\omega l d I^2 \quad (6)$$

where,

ω is the ac network angular frequency [rad/s];

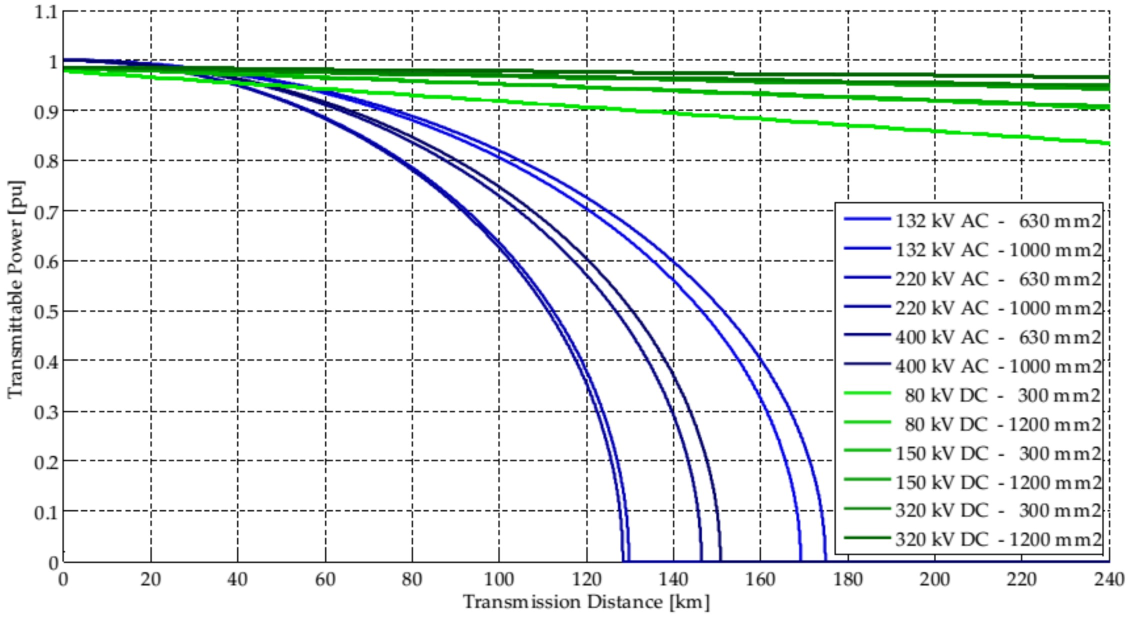


Figure 32: Maximum transferrable power as a function of transmission distance for AC and DC submarine cables.

c is the cable capacitance per phase per unit-length [F/km];
d is the transmission distance [km];
E_p is rated ac network phase voltage [V];
l is the cable inductance per phase per unit-length [H/km] and
I is the rated current through the cable [A].

On the other hand, dc cables do not suffer from leakage current of capacitive nature and thus, in steady state, the transmission of the electricity is only limited by the cable resistance, i.e. the Joule losses. The total active power which can be transmitted using a dc cable can be calculated as:

$$P_{dc} = P - 2rdI^2 \tag{7}$$

where,
P_{dc} is the dc cable transmittable active power [W];
P is the dc cable rated power [W];
r is the dc cable resistance per phase per unit-length [Ω/km] and
I is the rated current through the cable [A].

Table 3 provides typical parameters for HVac and HVdc submarine transmission cables [49,50], whereas Figure 32 depicts the normalized maximum transmittable power in relationship with the transmission distance in per unit of the cable power rating.

The current rating of a cable (also known as its ampacity) depends on several factors, such as the rated power, voltage, length, isolation method, burying depth, soil type and conductor type.

Surprisingly, between the ac cables, the 220-kV cables have the lowest maximum the transmission distance, while the 132-kV cables have the best performance. However, this needs to be further specified for each case study, taking into account laying costs, reliability etc. Nevertheless, after distances greater than circa 70 km, HVdc transmission systems are a better option, regarding losses and power ratings, for the connection of offshore wind farms [51]. This is a typical distance but is not the economic break-even point, which needs to be specified for each case study (see Figure 33).

Meanwhile, there are efforts to improve the voltage rating of submarine underground ac cables to voltages higher than 400 kV. While it is true that increasing the voltage augments the ac cable rated power, the cable reactive power generation grows with the square of the voltage - as shown in (6) - thus the problem of high charging current losses persists.

As future planned offshore wind farms tend to be build further away from the shore and become ever bigger in size, HVdc transmission becomes a better option and it will be increasingly difficult to keep using HVac transmission systems for the connection of offshore wind farms due to the need to provide reactive power compensation, which increases the transmission system costs.

Figure 33 shows a comparison between the costs for an HVac and an HVdc transmission system. When the distances and power involved are high, the use of HVdc transmission systems becomes justifiable since, even though they present a higher initial capital expenditure because mainly of the converter stations, they are cheaper in the long run due to the lower operational expenditure obtained from lower transmission losses.

Several studies have shown that for larger amounts of power (above 500 MW) and for long submarine transmission distances (above 70 km), the use of HVdc systems for the transmission of the generated electricity offshore is both economically and technically more convenient than using HVac systems [51-53].

Table 3: Typical parameters of HVac and HVdc submarine cables.

Cable type	HVac						HVdc					
Cable cross section [mm^2]	630			1000			300			1200		
Current Rating (Copper) [A]	715		1065	825		1290	797			1791		
Rated Voltage [kV]	132	220	400	132	220	400	±80	±150	±320	±80	±150	±320
Rated Power [MVA or MW]	163	189	272	314	738	894	128	287	239	537	510	1146
Resistance per phase [$m\Omega/km$]	—	—	—	—	—	—	60.1			15.1		
Capacitance per phase [nF/km]	209	238	151	177	130	160	—	—	—	—	—	—
Inductance per phase [mH/km]	0.37	0.35	0.41	0.38	1.40	1.35	—	—	—	—	—	—
Reactive Power @50 km [%]	30.6	30.1	37.3	37.4	37.3	37.4	0	0	0	0	0	0
Reactive Power @100 km [%]	61.2	60.1	74.6	74.8	74.6	74.8	0	0	0	0	0	0
Available Power @50 km [%]	95.2	95.4	92.8	92.8	94.1	95.5	94.1	95.5	95.3	96.0	95.3	96.0
Available Power @100 km [%]	79.1	79.9	66.7	66.4	91.2	94.2	91.2	94.2	93.7	95.2	93.7	95.2

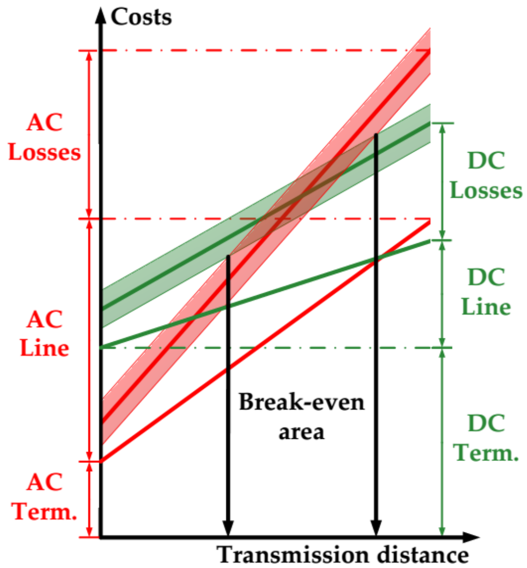


Figure 33: Cost comparison between HVac and HVdc transmission systems.

VSC

Introduction

The main objective of this section is to present the basic configuration of a voltage-source converter for high voltage DC transmission (VSC-HVDC) system. On the first part of the chapter, a short description of the main components of a typical VSC station is provided. Moreover, the basic control principles are illustrated and the related control equations are derived. The second part deals with the commercially available modular multi-level converter (MMC) concepts.

VSC background

Voltage-source converters were introduced for the first time to the HVDC transmission market in 1997 by ABB, for the experimental Hallsjon project in Sweden [54]. This link operated at 3 MW and ± 10 kV. After the successful test of the new HVDC transmission technology, the first commercial VSC installation was commissioned in 1999, for a system of 50 MW at a DC voltage of ± 80 kV, on the island of Gotland, in Sweden. Since then, the voltage and power ratings for VSC-HVDC applications have steadily increased, reaching nowadays a DC voltage level of ± 640 kV (bipolar) and a power capability of 2562 MVA.

A typical VSC-transmission system consists of an AC power transformer, AC filters, a phase reactor, the converter cabinet, which includes the switch valves, as well as one or two DC capacitors, DC harmonic filters and finally one or more DC cables and neutral point grounding depending on the configuration of the DC network. The layout of such a VSC-HVDC transmission system is depicted in Figure 34.

AC grid and AC breakers

Whether the connected AC grid is characterized as weak or strong, is mostly dependent on its short-circuit ratio (SCR), which is defined as the ratio between its apparent power and the

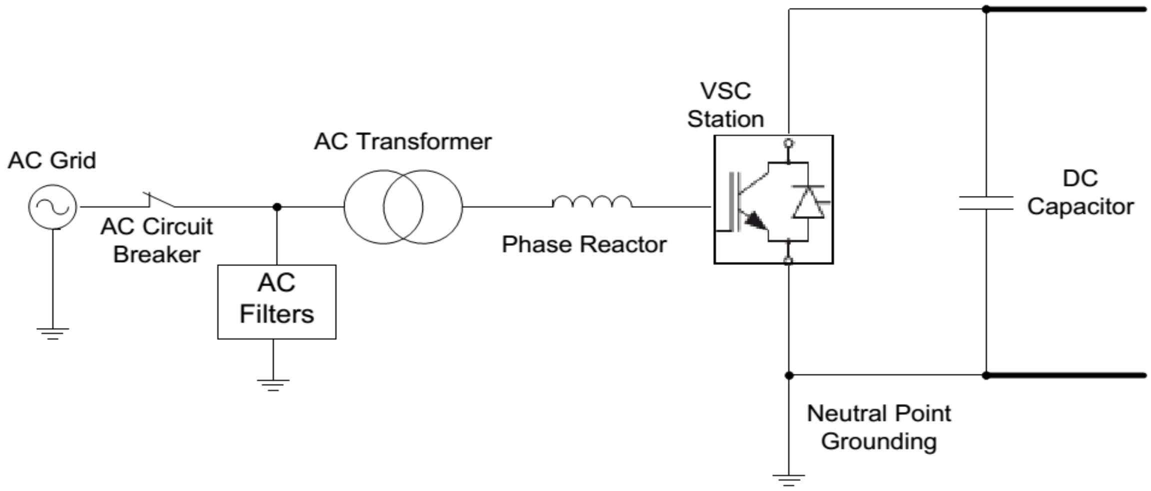


Figure 34: Single-line diagram of a VSC station.

apparent power of the VSC connected to it, i.e. $SCR=S_{AC}/S_{VSC}$. The higher the SCR, the stronger is the grid and thus the less are the grid voltage perturbations due to the exchanged power with the VSC. Finally, it is important to determine the grid's XR-ratio, which is the ratio between the grid reactance and its resistance. This is an alternative way of expressing the grid's short-circuit angle and its value is usually high for HVAC networks, in which reactance prevails (inductive grid).

In a VSC-HVDC station AC breakers are necessary because [55-57]:

- They are able to disconnect the VSC from the AC grid in case of emergency or maintenance;
- They consist the only so far applicable way to clear DC faults, as VSCs lack the inherent ability of classical HVDC systems to deal with DC contingencies;
- They can connect the AC grid to the VSC link in order to charge the DC capacitors during the start-up phase of the system.

However, although the technology of the AC breakers is mature enough to provide an inexpensive solution, its use has a main disadvantage. The converter safety cannot solely depend on them, as in case of a DC fault, the whole converter is forced to shut down for several milliseconds. This is inefficient, as the power exchange is interrupted for long times due to their mechanical restrictions and thus new more delicate solutions were investigated and are described in the following chapters.

Finally, a bypass resistor is usually used to limit the maximum phase current during the energization of the system. The pre-insertion resistors can be connected in series with each phase only for the start-up period. After the transient period is over, the resistors are bypassed to avoid extra losses and any effect on the control of the system. The resistor value depends on the system parameters and needs to be determined for each specific application.

Transformer

A power transformer is used to change the voltage level of the grid to the appropriate level for the VSC station. The transformer can be an ordinary three-phase power transformer and mainly provides a galvanic isolation between the AC grid and the DC side, which is important in case of a fault in either of the connected sides. Moreover, a transformer with primary grounding is commonly used. In this way zero-sequence voltages can be blocked by the ungrounded transformer secondary.

The use of a usual two winding transformer is further supported by the fact that, the current in the transformer windings contains hardly any harmonics and therefore the respective losses are low [58].

However, the transformer is not only exposed to AC voltage stresses, which are generally low, but also to DC stresses. If the VSC configuration of Figure 35a is considered, the DC potential on the valve side winding of the transformer is $+V_{DC}/2$. However, if the DC side is grounded in the middle point of the DC link, as in Figure 35b, the DC potential, to which the secondary of the AC transformer is subjected, is zero [59]. Therefore, the DC stresses and consequently the transformer insulation level depend greatly on the grounding of the HVDC grid topology and will be further discussed in section 2.5.

AC Filters

The main goal of the AC filters is to limit the harmonic content of the converter current and voltage, which can be detrimental for the whole system. The magnitude of the harmonic electromagnetic field (EMF) at the converter depends on the switching frequency, the DC voltage and the chosen PWM technique. In general, PWM moves the produced converter harmonics to the high-frequency spectrum, where they can be filtered more effectively. Consequently, the AC filters have to be designed as high-pass filters in order to cut those frequencies, which results in smaller AC filter sizes in VSC-HVDC compared to the classic HVDC (LCC). In this way the AC filters also protect the transformer from high frequency stresses, preventing harmonics from entering the AC grid. Since there is mainly high-frequency harmonic content the AC filters do not need to be more specifically tuned.

An important parameter, which most of the times is not specified, is the impedance of the grid to which the VSC is connected. However, the general requirements for the AC filters are [58]:

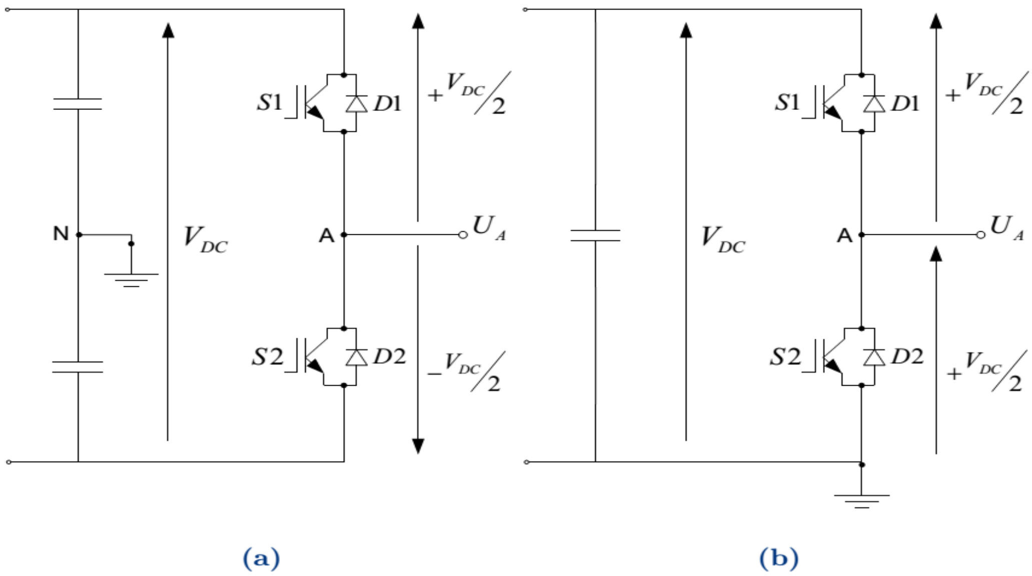


Figure 35: DC potential level of AC phase in case of (a) neutral point grounding (b) DC link middle-point grounding.

- Individual harmonic distortion:

$$D_h = \frac{U_h}{U_1} \approx 1\% \qquad (8)$$

- Total harmonic distortion:

$$THD = \sqrt{\sum_h D_h^2} \approx 1.5 - 2.5\% \qquad (9)$$

- Telephone influence factor:

$$TIF = \sqrt{\sum_h (5hf_1 C_{message(hf_1)} D_h)^2} \approx 40 - 50 \qquad (10)$$

Providing reactive power compensation for the HVDC converter is also a very important role performed by AC filters. A typical filter size is between 10 to 30\% of the required converter reactive power compensation.

Phase Reactor

The phase reactor, usually installed on the VSC-HVDC AC side, plays a multifaceted role for the converter. The phase reactor acts as a filter for the harmonic currents generated by the converter switching (low-pass filter). It prevents very fast changes in polarity that can be caused from the valves switching, while it limits short-circuit currents. An additional main purpose of the reactor is to permit independent and continuous control of active and reactive power, by controlling the voltage drop and the direction of the current flow across itself. A common size for the phase reactor is 0.15 pu [58].

Voltage Source Converter

A typical VSC uses fully-controllable switches, like gate turn-off thyristors (GTOs) or IGBTs, in contrast to the LCC, which makes use of line-commutated thyristor valves. Fully-controllable switches are preferred for high voltage applications with relatively high switching frequencies (~2 kHz). The switches are mostly controlled with PWM techniques to reproduce a sinusoidal waveform on the AC side, which is filtered by the phase reactor and the AC filters. As a result, the harmonic content of the reproduced waveform is kept low. A two-level converter is the simplest topology that can be used to build a three-phase VSC. For this converter topology, six switch valves are used which contain several switches in series depending on the voltage and the current ratings anti-parallel diodes accordingly, to facilitate the bidirectional power flow of the converter. A typical layout of a two-level three-phase voltage-source converter is presented in Figure 36.

The operating principle is simple; each of the phases is connected via the switches either to the positive or the negative pole of the dc grid. By controlling the width of the pulses via PWM techniques, a sinusoidal waveform is reproduced. As a consequence, the more the levels of switching valves that are connected in each of the arms of the converter, the lower the harmonic content of the AC waveform will be.

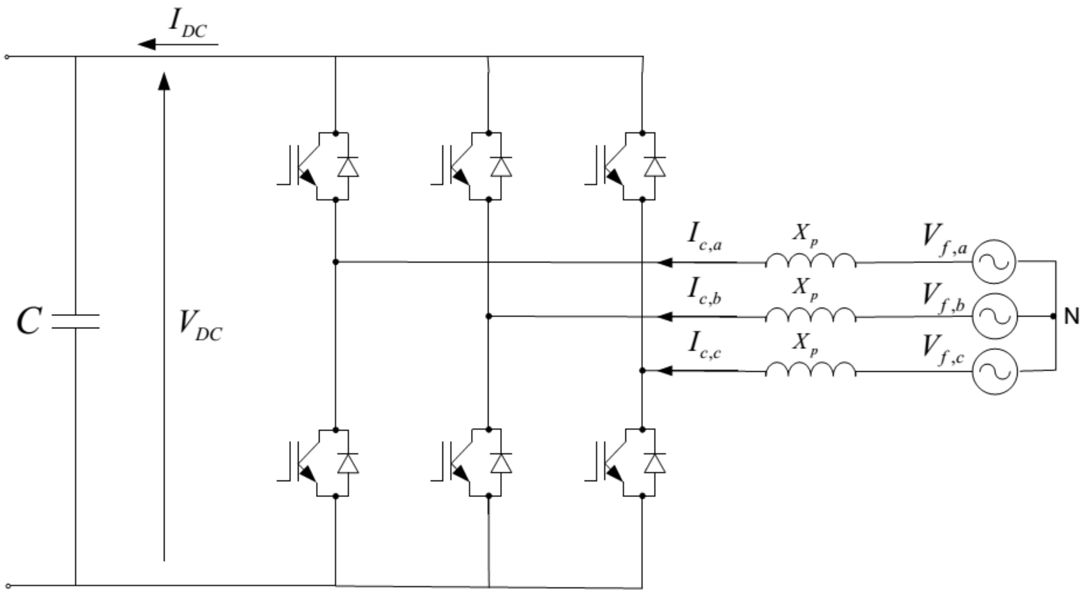


Figure 36: Two-level three-phase converter.

DC Capacitor

The DC capacitor is used to maintain the DC side voltage at a specific level and within very close limits, thus acting as a voltage source. The primary purpose of the capacitor is to provide a low-inductance path for the turn-off current, to serve as energy storage and to reduce the harmonic ripple of the DC voltage.

However, the size of the capacitor influences the power flow control, the stiffness of the controllers and their bandwidth. In VSC-HVDC links, the DC capacitors consist the main inertia source and thus their size has to be carefully calculated, based not only on the steady-state operation, but basically based on the desired transient behavior, e.g. during faults or changes in operating power point, in order to avoid unwanted overvoltages at the converter valves.

The DC capacitor can also be divided into two capacitors connected to a neutral point, which can either be clamped to the neutral of the converter and grounded, or only grounded. In this way, the DC capacitor serves its goal as a path for the turn-off current to the ground. The DC capacitors' configuration depends on the DC grid topology, which is further discussed in section 2.5.

The DC capacitor can be characterized by a time constant τ. This constant represents the necessary time to fully charge the capacitor at the converter nominal power and is defined as the ratio of the energy stored in the capacitor, when rated voltage (V_{DC}) is applied to it, with respect to the converter's nominal apparent power S_n.

$$\tau = \frac{1}{2} C \frac{V_{DC}^2}{S_n} \tag{11}$$

If the mechanical analog of the DC capacitors in a VSC-HVDC link is considered, the time constant τ corresponds to the machine inertia constant H [sec]. More specifically, H is given by [60]:

$$H = \frac{W_k}{S_g} = \frac{1}{2} J \frac{\omega^2}{S_g} \tag{12}$$

where W_k [MVA·sec]is the kinetic energy stored in the rotating mass of the machine, S_g [MVA] is the generator rating, J is the moment of inertia [kg·m^2] and ω [rad/s] is the

generator's angular speed.
The analogy of the two constants is backed up by the dimensional analysis of the equations. The mechanical analog of voltage [V] is velocity [m/s], while the respective analog of capacitor [F] is the mass [kg]. As a result, the kinetic energy in the rotating part of the generator is equivalent to the electrostatic energy stored in the capacitor.

Furthermore, the machine inertia constant H determines the response of the generator's angular speed to any changes in the input power. Equivalently, the capacitor's time constant determines the response of the DC voltage level to any power changes. Therefore, the DC capacitors play the role of the machine inertia in VSC-HVDC systems.

Controllers

The main capability of a VSC is the independent control of active and reactive power flow. As mentioned in the previous section, by controlling the phase angle δ and the amplitude of the converter voltage, active and reactive power can be independently adjusted.

Reactive power control is possible through direct control and AC voltage control. In the direct reactive power control, reactive power is compared to a reference value. The PWM modulation index (m_α) is controlled to make the converter absorb or generate the necessary amount of reactive power.

In case of AC voltage control, the actual AC voltage level at the converter is compared to a reference value. If it needs to be lowered, the converter absorbs reactive power. On the contrary, if the AC voltage needs to be increased, the converter generates reactive power.

As far as real power is concerned, it can be controlled in three ways:

- directly;
- by controlling DC voltage level;
- by controlling AC frequency.

The direct active power control is accomplished through setting the phase angle of the fundamental frequency component of the VSC voltage.

In the DC networks active power flow should be balanced at all times. A possible unbalance in the active power causes rapid changes in the DC voltage level, which can be prevented by controlling it. Due to such unbalances, it is considered essential to use DC voltage control at least in one of the VSC stations in a two- or more terminal network. In this way, balanced active power flow can be ensured and the amount of real power needed to be fed or absorbed to sustain the required voltage level at the DC capacitors is always regulated.

In addition to the previous two control mechanisms, AC frequency control is necessary in case of VSC connection to a weak grid or passive loads. The control is achieved through changes in the frequency of the valve pulse firing sequence in PWM. By regulating the amount of active power exchanged with a weak grid, VSC can support the grid frequency, damping any frequency oscillations.

Another important VSC control is the AC current control that flows to/from the converter through the phase reactor. The inner current controller (ICC) regulates the current to a reference value, by evaluating the required voltage drop across the phase reactor, without exceeding the maximum current limitation of the converter. The reference values for the current are provided by the outer controllers and the role of the ICC is to evaluate the necessary voltage drop over the series reactance to produce the reference current.

The outer controllers consist of the all the previously discussed controllers used for active and reactive power control. However, the controller choice depends on the VSC network and on each project's specifications. Figure 37 shows the overview of a VSC system's control structure.

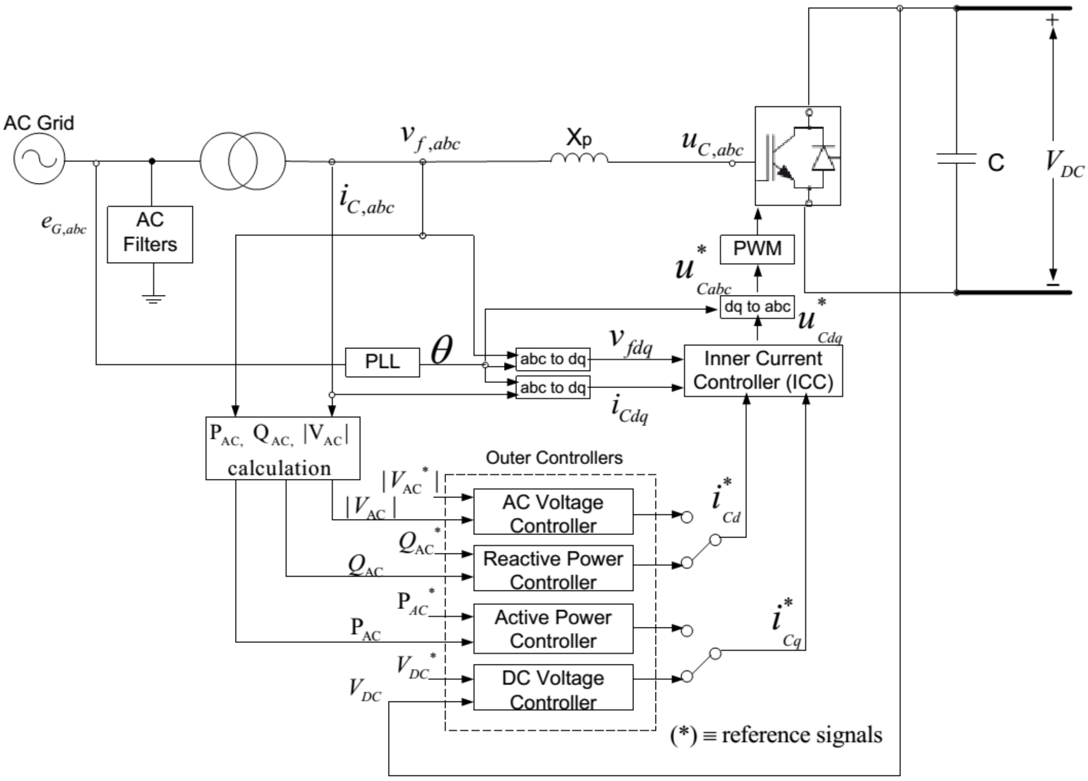


Figure 37: VSC controllers overview.

To facilitate the system's control, all the three-phase voltages and currents are transformed into the direct-quadrature coordinate system (dq). This transformation is called the Park Transformation. However, in case the dq-frame representation is used, the new coordinate system needs to be synchronized with the AC network. This is achieved through a phase-locked loop control (PLL).

Multilevel Modular VSCs

In 2003, Professor Marquardt from the Technical University of Munich [61] proposed the concept of modular multi-level converters (MMC).

The proposed converter consists of three phase units. Each phase unit comprises two converter arms, each with a converter module and a converter reactor. Each converter module consists of numerous power modules connected in series, whose number depends on the application. Each power module contains two or four IGBTs as the switching elements, depending on the design (half bridge or full bridge), a DC storage capacitor and other valve firing electronics.

Unlike other VSC topologies, there is less difficulty in connecting modules in series with this converter topology. The converter number of levels can simply be increased by connecting more submodules in series. Hence, the submodules are the elementary building blocks of the MMC system.

The main advantage of this topology is the fact that since there are n-1 capacitors stacked, n-1 respective voltage levels are available to synthetize the desired n-level AC voltage. Therefore, the AC voltage created has an almost perfect sinusoidal shape and the filtering or smoothing needs are minimum. At the same time, the voltage derivative is very low, resulting in less stresses on the switches and on the phase reactor and less produced EMI.

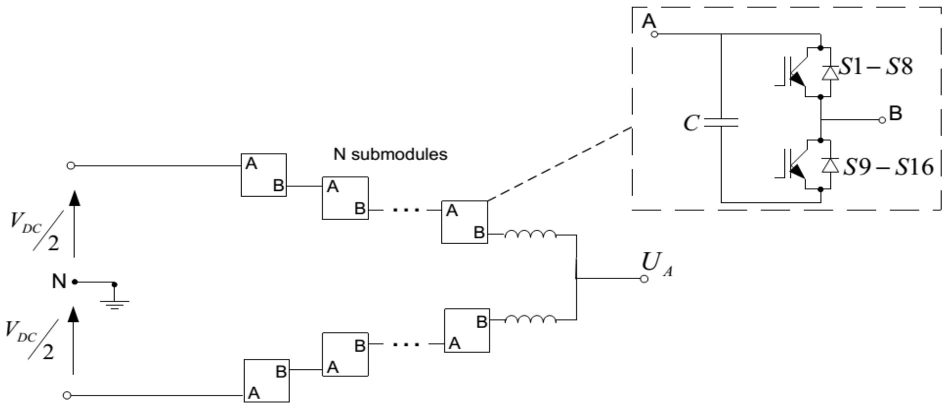


Figure 38: ABB HVDC LIGHT topology and half-bridge submodule.

Moreover, the more levels are introduced, the lower the switching frequency which results in less switching losses in the converter and increased overall system efficiency. On the other hand, more complex structures with more switching elements increase control complexity and introduce higher system costs.

Three companies currently offer HVDC modular multi-level converters: ABB, Alstom and Siemens. Next, an overview of the different commercially available technologies is given.

ABB HVDC LIGHT

ABB introduced the concept of a cascaded two-level converter in 2010 [62]. The operating principle is the same as the modular multi-level converter, however a different name is used to stress that their solution of press-packed IGBTs, used for two-level converters, is extended to accommodate the increase of converter levels. More specifically, press-packed IGBTs are connected in series to form the converter phase arm. The valves are connected as shown in Figure 38.

From Figure 38 it can be seen that half-bridge modules, consisting of eight IGBTs in series per submodule pole and one capacitor are used as primary blocks. These are then connected in series to create each phase arm. Inside each submodule, ABB introduces series connection of devices also in the multi-level converter. In this way it supports the redundancy of the system and avoids system failure in case a single device experiences a problem. In case one switch fails, the rest in the same pack are able to share the slightly increased voltage and operation is continued without interruption. The IGBT that failed enters a short-circuit failure mode (SCFM), which means it can carry the load current until the next maintenance takes place [63].

Another important fact is that the switching frequency of each cell is approximately 150 Hz, which is only three times higher than the AC system fundamental frequency. The effective switching frequency per phase leg can be calculated by multiplying the cell switching frequency by the number of employed cells. As a result, the dynamic response of the converter is very good, while at the same time the overall losses are kept low, circa 1% [64].

Siemens HVDC PLUS

Siemens was the first company to introduce the M2C technology for HVDC applications. Based on the original concept of Professor Marquardt [61], each converter arm operates as a

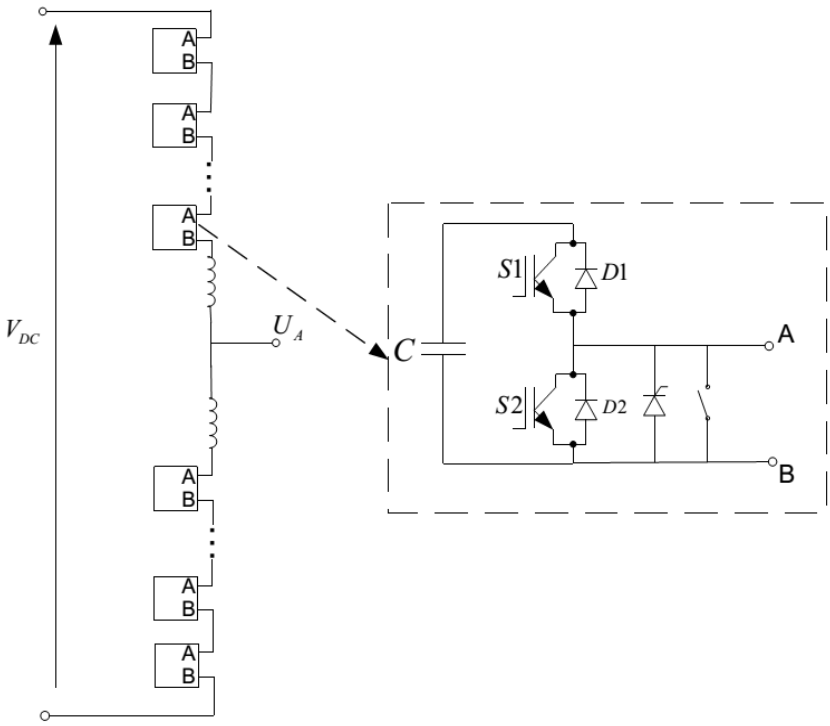


Figure 39: SIEMENS HVDC PLUS topology and half-bridge submodule.

controllable voltage source with as many voltage steps as the number of submodules. Each converter phase arm is built by submodules, which are identical, but controlled individually. The HVDC PLUS configuration is shown in Figure 39 [65].

The power submodule contains an IGBT half bridge and a DC capacitor for energy storage. Depending on the way the submodule is switched, the capacitor is either bypassed or connected in series to the phase current. The switching states of half bridge modules will be further explained in section 4.3.1.

In case of a module failure, the system should be able to withstand the fault and not interrupt the energy transfer. Therefore, a high-speed bypass switch is implemented, which is turned on in case of an emergency reliably by-passing the module. In this way, operation is not interrupted and the excess voltage stress on the rest of the arm modules is equally distributed.

Moreover, equal voltage distribution is ensured through periodic control of the capacitor voltage on each module. When necessary, selective switching of power modules can be used to balance the voltages between the submodules.

Additionally, phase reactors are connected at each phase arm in order to reduce the fault currents and their rate of rise, in case of faults within or outside the converter, as well as to reduce balancing currents between the phase units.

Finally, each submodule has a press-pack thyristor, which is used in case of DC faults to protect the free-wheeling diodes of the switches till the AC breakers open. The response of half-bridge modules to DC faults is further explained in section 4.3.

Alstom HVDC MAXSINE

Alstom has also developed a modular multi-level converter, known as HVDC MAXSINE. The operating principle is the same as the MMC, however, unlike the previous two solutions which use half-bridge modules in their converters, Alstom has developed full-bridge modules, mainly driven by the need to provide a solution for the DC fault handling problem. In Figure 40 the general scheme of HVDC MAXSINE is given.

As with Siemens HVDC Plus, connecting a number of submodules in series, creates the multilevel circuit. The number of series connected submodules depends on the application.

The submodule, shown in Figure 40, contains full-bridge IGBTs as switching element (cooled by water heat sinks) and the DC capacitor (oil free design). In case a submodule fails, a mechanical switch is used to short-circuit and successfully provide uninterrupted energy transfer.

However, the use of full-bridge modules increases the number of semiconductor switches used in the design, thereby resulting in higher cost as well as higher losses (1.3-1.4%) than the half-bridge modules [66]. In order to overcome this problem, Alstom has proposed a hybrid topology, which is presented in Figure 41 [66,67].

This hybrid series connected converter tries to combine the advantages of half-bridge modules (low harmonic distortion and low losses) with the DC fault response of full-bridge modules. Series connected IGBTs are arranged to form the converter and they are used as director switches. The full-bridge modules are then switched in a way to produce the desired AC voltage waveform which meets the requirements of the grid. The full-bridge IGBTs are switched at the frequency of the AC supply, but also at near zero voltage, which decreases significantly the switching losses. More specifically, the positive cycle of the sinusoidal waveform is constructed by the upper arm whereas the negative cycle is produced by the lower arm. At the same time, the converter is still very responsive to faults and it has the capability of blocking the DC fault current [68].

Finally, in VSC-HVDC transmission links there is not usually the need to invert the DC voltage of the converter. However, Alstom claims that by using the hybrid MMC topology with full-bridges it is possible to reverse the voltage on the DC-side of the VSC, making it easier to operate this converter alongside LCC-HVDC [69].

CSC-HVDC

The world first commercial solid-state HVdc system was commissioned by General Electric in 1972, as part of a contract for the Eel River link in Canada (contracted in 1969) providing an asynchronous connection between Hydro-Quebec and New Brunswick Power [42,70]. The converter station had a back-to-back configuration and its power rating was 320 MW at a voltage of 160 kV.

After improvements in thyristor valves, larger powers could be transmitted via HVdc transmission systems through longer distances. The thyristor technology is nowadays very mature and there are over 140 Classic HVdc transmission systems installed worldwide [42].

Figure 42 shows the evolution in the thyristor technology for HVdc Classic and the accumulated HVdc installed capacity worldwide, including projects yet to be commissioned until 2015 [42,71].

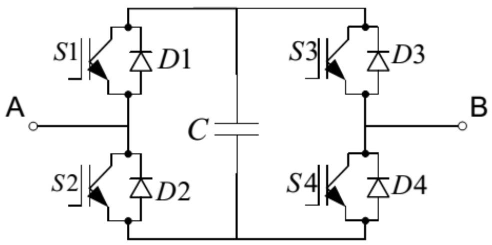


Figure 40: Alstom HVDC MAXSINE full-bridge submodule.

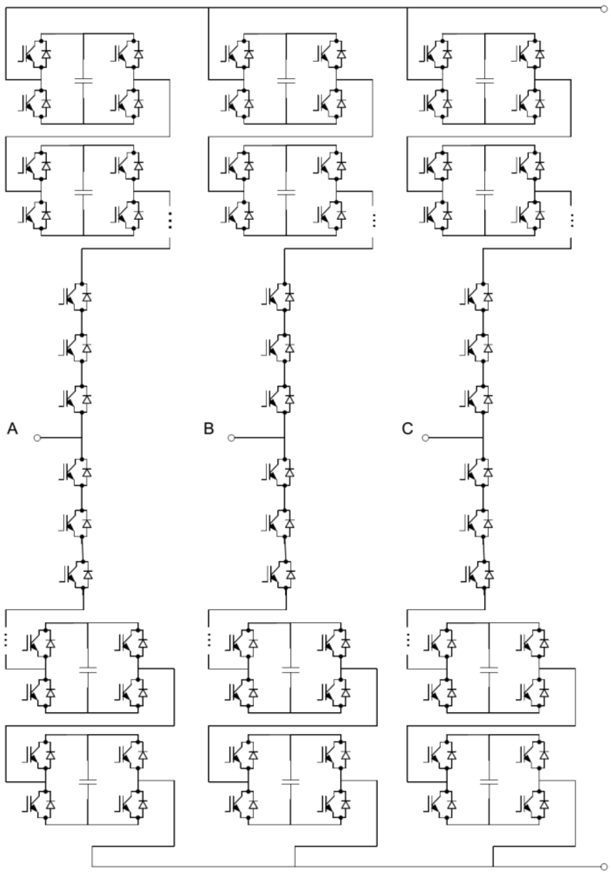


Figure 41: Alstom hybrid series connected topology.

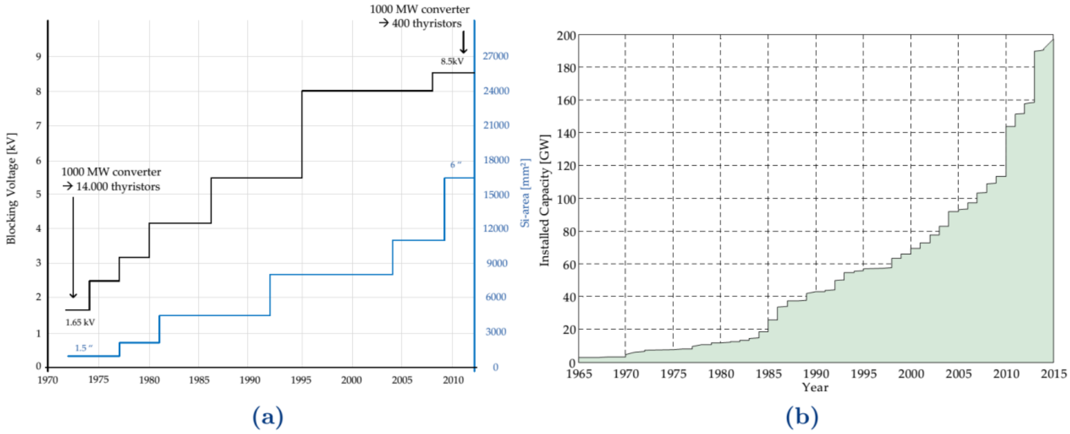
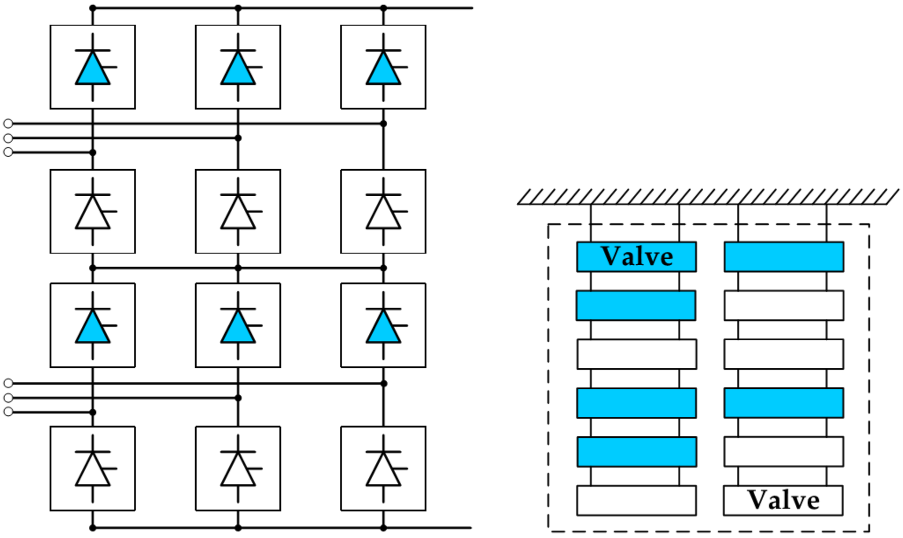


Figure 42: Evolution of HVdc systems: (a) thyristor technology (b) worldwide installed capacity.

HVdc Classic Station

In a HVdc Classic station, a large number of thyristors need to be connected together to build a converter valve module capable of withstanding the voltage levels required for HVdc



(a) Converter topology (b) Valve physical arrangement

Figure 43: CSC-HVdc converter.

transmission [70,71]. Figure 43 shows a typical valve arrangement in a 12-pulse CSC-HVdc system and the valves physical arrangement, which hangs from the HVdc Classic station ceiling to improve seismic reliability.

Modern HVdc valves, such as the one shown below in Figure 44, make use of light-triggered thyristor (LTT), which can be triggered via a fiber optic cable permitting elimination of auxiliary power circuits, gate pulse amplifiers, gate drive units and pulse transformers at thyristor potential. With no need of electronics at HV potential and with fewer components the resulting valve module has increased reliability [71].

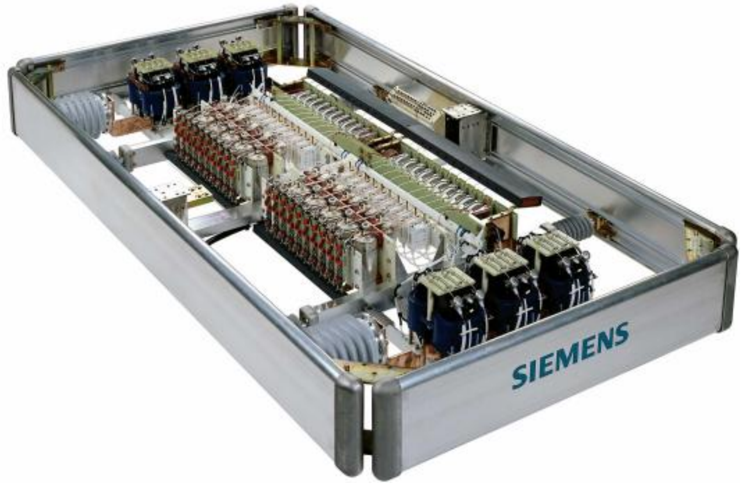


Figure 44: A typical LTT HVdc valve module.

For HVdc projects with high power ratings and voltage levels, multiple 12-pulse bridges can be used to help further reducing the harmonic components of the ac-side current and the dc output voltage. Using multiple bridge converters, e.g. the 24-pulse or 48-pulse configuration, the harmonic performance of the HVdc transmission system is improved, reducing filter costs [36]. In a 12-pulse HVdc configuration, one of the converter bridges is connected to the ac grid using a transformer with YY0 winding configuration, while the other converter bridge will be connected to the ac grid using a transformer with YD5 winding configuration. Hence, the two converters will have each an ac three-phase phasor, but shifted by 30 degrees with respect to each other. As a result of this phase shift between the ac three-phase voltages, the characteristics harmonics of an idealized 12-pulse bridge are 12n for the direct voltage and (12n ± 1) for the AC current (n ∈ N*). The fact that multiple bridge converters require less filtering is the main reason why almost all modern HVdc systems make use of such configurations. However, transformer connections to provide the necessary phase shift become more complex and the converters are more difficult to justify economically.

The HVdc converters represent the heart of the transmission systems as they are responsible for the actual ac-dc and dc-ac conversion. However, there are other main components that integrate an HVdc transmission scheme. They perform several necessary tasks for proper system operation, reliability and compatibility with the surrounding environments.

A typical HVdc transmission arrangement, with a 24-pulse converter arrangement, can be found on Figure 45, where the main components are indicated [36]. The numbers on Figure 45 correspond to the following components:

1. Converter bridges;
2. Converter transformers;
3. Smooth reactors;
4. AC filters;
5. Reactive power supply;
6. DC filters;
7. Surge arresters;
8. Neutral bus surge capacitor;
9. Fast dc switches;
10. Earth electrode;
11. DC line.

The Future of HVdc Classic

Most HVdc Classic transmission systems have distances between 180 and 1000 km, with voltages between 500 kV (± 250 kV) and 1000 kV (± 500 kV) and power ratings between 500 and 2500 MW [41,42,72].

The HVdc Classic technology is undisputed when it comes to bulk electric power transmission and ratings up to 7.2 GW are possible using 1600 kV (± 800 kV) transmission systems - known as ultra-high voltage (UHVdc) - such as the transmission link between Jinping and Sunan, which is currently being constructed in China, when finished will be the largest dc transmission system in the world [73]. However, as was the case with mercury-arc valves, it is only possible to control the moment when thyristor valves turn on, but not when they turn off. The thyristor conduction has to be stopped externally by the ac network, which is why this type of HVdc converter is also known as line-commutated converter (LCC-HVdc). The fact that the HVdc Classic is line-commutated means it can control its active power flow but it always consumes reactive power. Moreover, depending when the thyristors are turned on, the reactive power compensation needs to be circa 50-60% of the converter rated power [36]. Hence, HVdc Classic transmission systems require, for proper converter operation, strong ac networks capable of providing the necessary reactive power. Table 5 shows a comparison between different characteristics of the CSC and VSC-HVdc technologies.

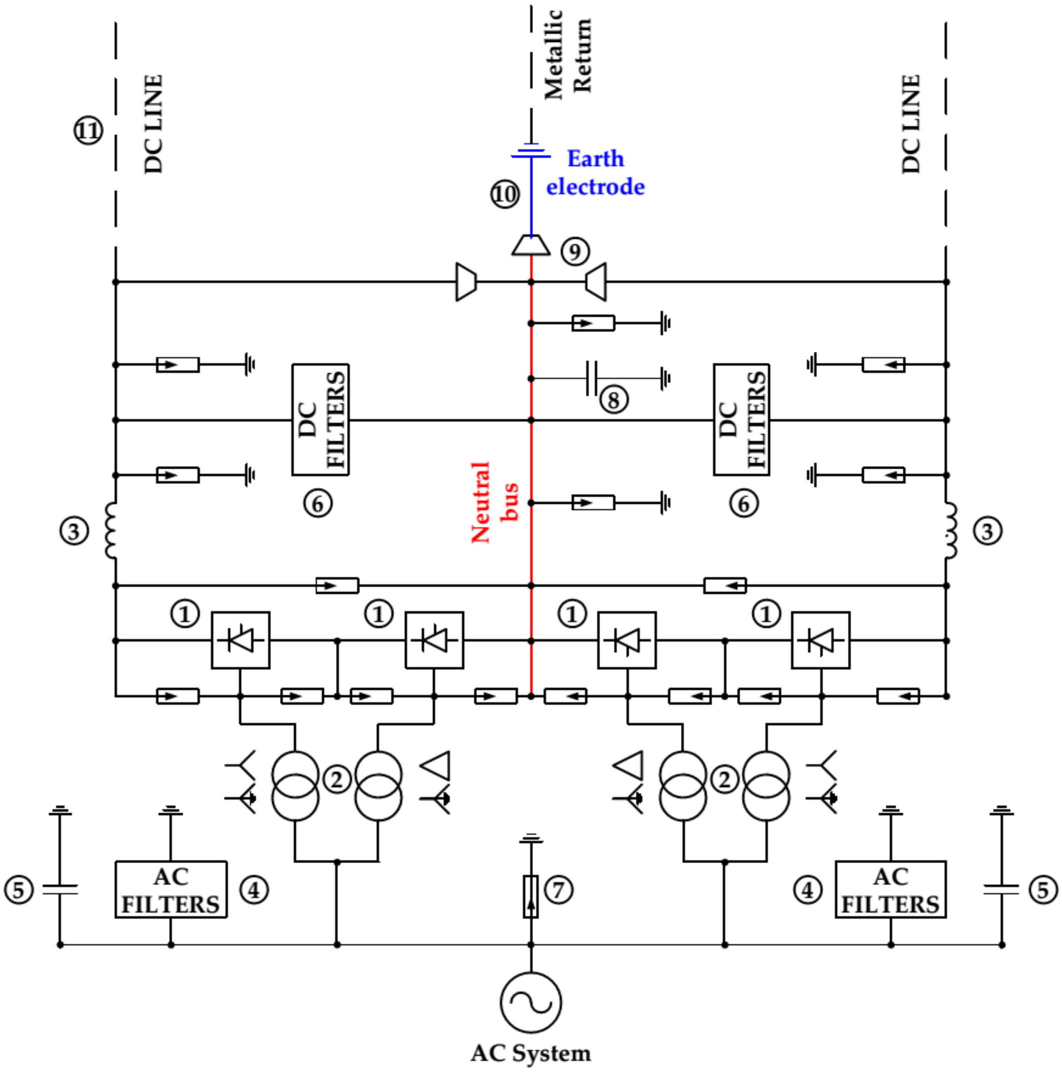


Figure 45: HVdc transmission system with 24-pulse converter arrangement.

Usually, part of the reactive power is provided by capacitor banks installed on the ac-side of the HVdc transmission system. However, due to its low switching frequencies, filters and related ac switch-yard considerably increase the footprint of Classic HVdc systems, making them improbable for offshore wind farm installations. Nevertheless, more than 270 GW of HVdc Classic transmission lines are predicted to be installed in China alone between 2010 and 2020. Figure 46 displays the evolution of CSC-HVdc systems [41,42,72].

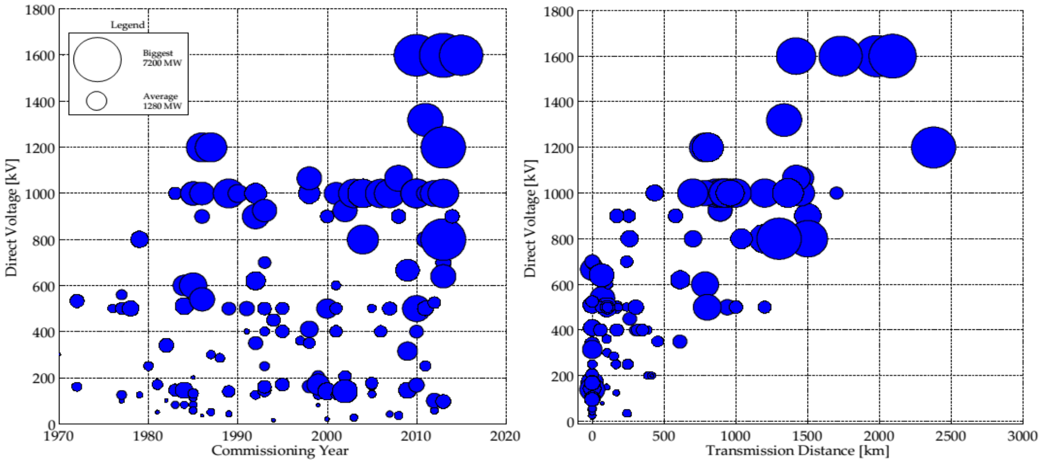


Figure 46: Evolution of CSC-HVdc transmission system voltage.

Configurations

Introduction

HVDC links have been operating around the globe for more than half a century. The first commercial link was made in 1954 to connect the island of Gotland to the mainland of Sweden. Based on the classical LCC-station, most of those links are point-to-point, while only two multi-terminal LCC-HVDC systems exist with three hubs interconnected [58,74]. The two multi-terminal HVDC links currently in operation are [75]:

- the Sardinia-Corsica-Italy (SACOI), interconnected the two islands with the mainland of Italy;
- the Hydro Quebec - New England link in Canada.

One of the main advantages of VSC technology in comparison to the classical is its capability to easily facilitate large multi-terminal networks. This is possible, due to their high controllability and thus the low levels of interaction between the interconnected terminals. This feature is essential for the new era of HVDC transmission systems in an attempt to reinforce the existing AC infrastructure and effectively connect not only national grids with the available offshore wind supplement, but also interconnect countries, providing cost-effective and reliable solutions.

Therefore, the analysis of the operation of all the possible network topologies on a real multi-terminal network consisting of VSCs is essential not only for normal operation, but also for protection analysis, especially when it comes to DC contingencies. In this section an overview of the existing topologies with their respective advantages and disadvantages is provided.

Operating Topologies

There are several possible converter arrangements in a HVDC transmission system, which can be divided, based on the number of converters used at each terminal, into monopole and bipole configurations.

Monopolar configuration uses only one pole, while the bipolar uses two poles with different polarities ($\pm V_{DC}/2$). These topologies can be further classified by the DC circuit characteristics, e.g. return path. It is important to stress that all the presented topologies can be extended to accommodate multi-terminal HVDC networks. Table 4 summarizes the most common operating topologies [56,76].

Table 4: Operating HVdc configurations

	No. of converters	
	Monopole	Bipole
Return path	Symmetric	Ground electrodes
	Ground return	Metallic neutral
	Metallic return	

Monopolar HVDC configuration

In this topology only one converter is used at each end of the network. Because of this characteristic, this method is more cost effective, but also more prone to problems. The HVDC grid lacks DC fault redundancy, as all of the interconnected stations are affected by the high fault currents and no power can be exchanged. Unless selective DC protection methods are implemented, which are able to isolate the faulty HVDC line in time, the grid has to get de-energized before operation is restored.

There are mainly three types of monopolar configurations:

1. Symmetric monopole, which uses two fully insulated conductors for the positive and return pole of the DC grid.
2. The asymmetric with metallic return has two DC conductors between the terminals, one of which is also grounded.
3. The asymmetric with ground return has only one DC conductor connecting the terminals and the return is made through the ground. All connected terminals need to be grounded.

Symmetric Monopole

Figure 47 depicts the symmetric monopole DC grid scheme. This configuration either uses no grounding on the DC side or the DC link capacitors are grounded in their middle point to fix the DC voltage. Therefore, in case of a DC pole-to-ground fault, the DC side is not fed by AC grid currents. Due to lack of DC grounding or the particular middle point grounding of the DC link, the coupling transformer is not subjected to any DC voltage and thus it does not suffer from increased voltage stresses. Therefore, its design can be simple. Moreover, there is no DC current in the ground, which can raise environmental issues. However, its main disadvantage against the other monopolar topologies is that it requires two fully insulated conductors, which increases its cost.

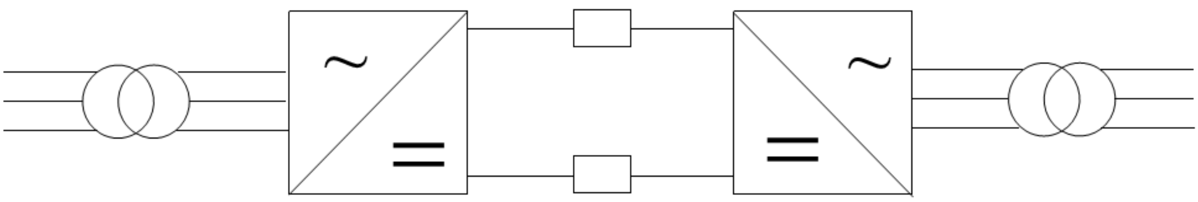


Figure 47: Symmetric monopole.

Asymmetric Monopole with Metallic Return

The configuration, presented in Figure 48 has no DC ground current, as the return is made via the metallic conductor, while at the same time it requires only one fully insulated conductor and one less, reducing its cost. Moreover, it can easily facilitate the expansion of the network to bipolar, as the metallic return can be used as neutral connection. On the other hand, the DC voltage stress on the coupling transformer is high. The transformer lies at 0.5 pu DC voltage and thus, it needs to be designed for higher DC voltage stresses than the one in symmetric monopole.

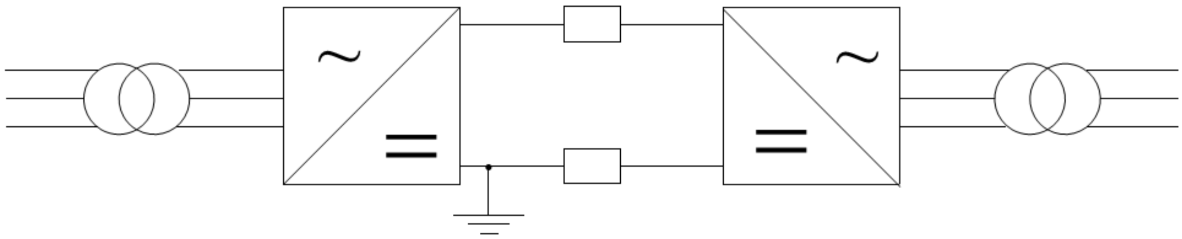


Figure 48: Asymmetric monopole with metallic return.

Asymmetric Monopole with Ground Return

This topology has the advantage of very low cost, due to the presence of only one fully insulated conductor and the capability of expansion to bipolar if necessary. However, except for the disadvantages of asymmetric monopole with metallic return, it requires permission for introducing electrodes to the ground and for continuous operation with DC ground current. As a result it raises environmental concerns, because the direct currents can interact with metallic structures in its vicinity. Therefore, a more careful design is necessary.

Additionally, the coupling transformer insulation levels need to be high, due to the DC voltage stresses to which it is exposed. The DC voltage level, at which the secondary of the transformer lies, is the same as for the asymmetric monopole with ground return. Finally, in case of DC faults, the AC side continues to feed the fault with in-feed currents, due to the loop created by the grounds at different points of the grid. Figure 49 presents the discussed topology.

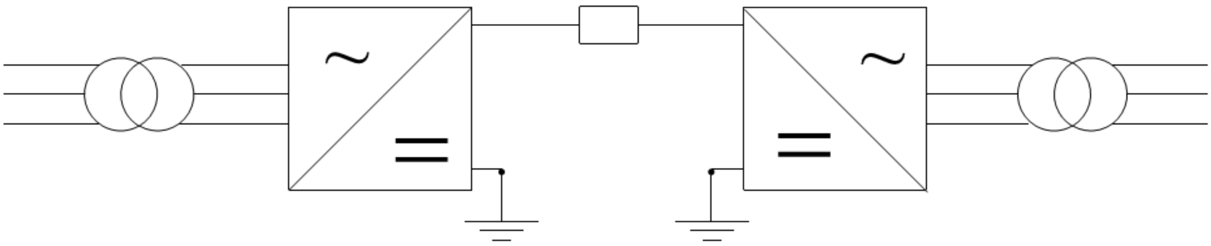


Figure 49: Asymmetric monopole with ground return.

Bipolar HVDC configuration

The bipolar configuration employs two converters at each terminal. On the AC side they are powered either by two different transformers, or by a transformer with two secondary windings. It is common to use Yg-d configuration for the positive pole converter and Yg-y for the negative pole converter or vice versa. The DC stresses on the transformers' secondary windings are high, as both of the transformers lie at 0.5 pu DC voltage. Therefore, a special attention has to be paid to their insulation.

On the DC side, each of them controls half of the DC voltage ($\pm V_{DC}/2$) and are connected to one or two DC in series capacitors. The current on each pole is roughly the same, with only small unbalances. The main advantage of the bipolar configuration is its redundancy, which can be even more than half the total station rating if overloading is possible, in case one converter suffers a fault. However, there are disadvantages for each of the available bipolar topologies.

Bipole with metallic neutral

This configuration is shown in Figure 50. As long as the DC side has a ground at the neutral, the transformers need to be designed for high DC voltage stresses. This fact along with the use of more converters makes them a more costly alternative than the monopolar ones for the same power rating, however bipolar configurations can achieve double the power rating of monopolar links.

Moreover, this bipolar configuration needs an extra low-voltage insulated neutral inductor, in comparison to the bipolar with ground return. There is also the possibility to use a fully insulated conductor and use it as spare in case of emergency, providing a more expensive solution.

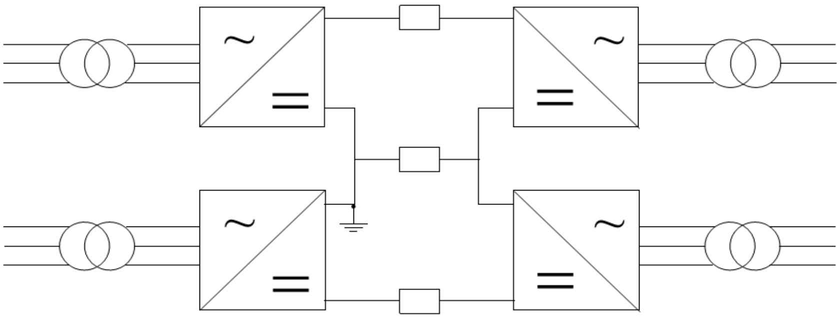


Figure 50: Bipole with metallic return.

Bipole with ground return

Except for the higher cost when compared to respective monopolar configurations, the bipolar configuration with ground return also raises environmental concerns, same with those of the asymmetric monopole with ground return. This HVDC topology is depicted in Figure 51.

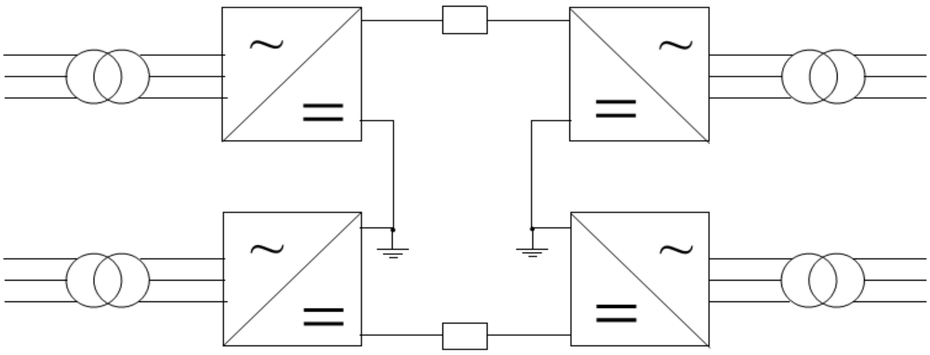


Figure 51: Bipole with ground return.

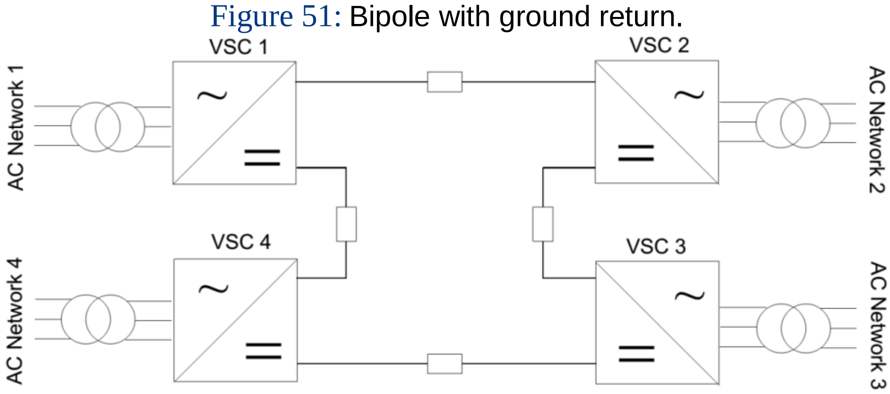
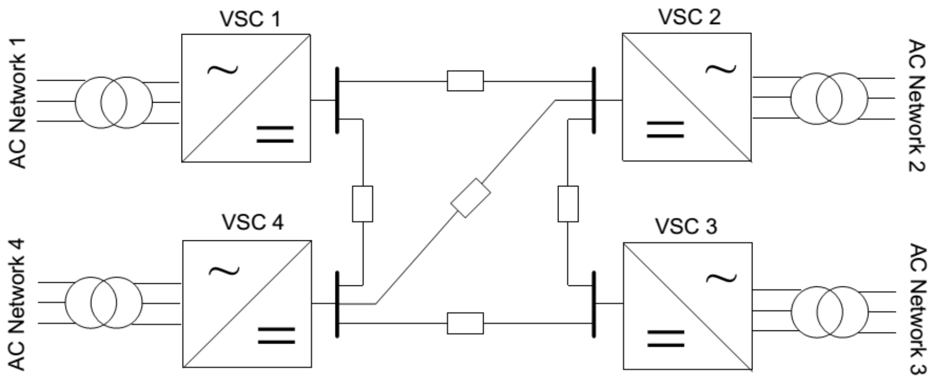


Figure 52: Series connection of MTdc network.

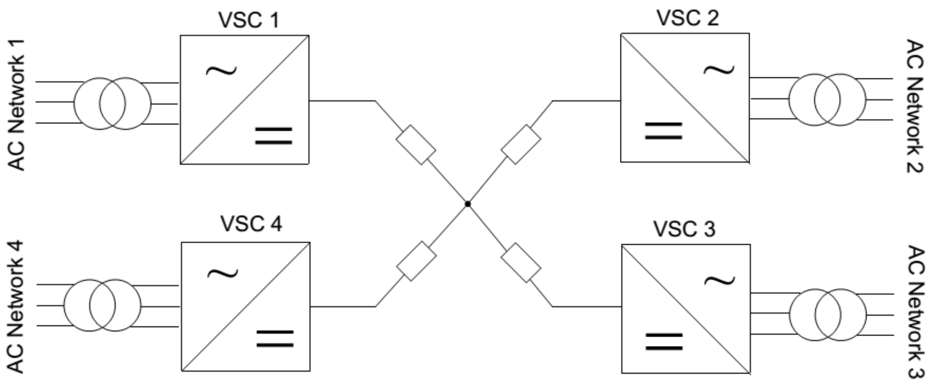
Multi-terminal DC network configurations

HVDC systems can be design to have additional taps configuring a multi-terminal arrangement. The multi-terminal can be series and have constant current or parallel with equal constant voltage and hybrid connections are also possible.

A series-connected MTDC system is shown in Figure 52. The converters are connected in series to form a single loop transmission system. The current remains constant and power flow is controlled by controlling the DC voltage across each converter. In case of emergency or maintenance, a converter can be removed by simply short-circuiting its DC terminals. Therefore, the system reliability is high [77].



(a) Meshed HVdc connection



(b) Radial HVdc connection

Figure 53: MTdc parallel configurations

However, there are several drawbacks that need to be considered. The most crucial is the excessive losses at light loading, due to the constant-current operation. Moreover, insulation coordination is difficult, as each ungrounded converter terminal in the HVDC system must be insulated from ground. Series connection allows grounding at only one point, and thus, the ungrounded converter terminals are all at various high-voltage levels. Consequently, each converter and transformer should be insulated for the highest possible voltage. This insulation substantially increases converter costs [77].

Regarding parallel MTDC configurations, there are two possibilities: the radial and the meshed connection. In the radial system, there is only one electrical path between any two converters. On the other hand, the mesh connection has more than one electrical path between converters. This parallel path makes the mesh system more reliable than the radial system.

The additional path in a meshed system allows for a line to be isolated safely, since the remaining lines have sufficient overload capacity to carry the load its load. When the line is opened, load-flow simply redistributes on the remaining lines, providing for an uninterrupted power flow. This action, however, requires a DC breaker. Moreover, through load flow optimization at the parallel paths of a meshed topology, the line losses can be minimized [77].

Considering a radial system, a line can be opened by using system controls to reduce the line current to almost zero and then disconnecting the line without the need of expensive DC breakers. Simple schemes of meshed and radial HVDC configurations are given in Figure 53.

2.3.2. Combining CSC/VSC

Several studies have investigated the possibility of a hybrid LCC/VSC connection, mainly in point-to-point connections [78-80]. The hybrid configuration is claimed to combine advantages of both technologies, classical HVDC and VSC. The most important advantages are [81-83]:

1. the reduction in the investment cost, as several HVDC projects already in place use LCC-HVDC technology;
2. the reduction in the power losses, due to the use of less VSCs in a multi-terminal network;
3. feasibility for high power levels resulting from the use of LCC, which is a mature technology;
4. higher controllability derived from the VSC converter controllers;
5. higher voltage stability through the voltage support of the VSC-HVDC link;
6. a more reliable power supply, since VSCs and LCCs can complement each other on the supply of nominal power;
7. the interconnection of weak and passive networks due to the use of VSC technology;
8. no full-rated dc breakers are required.

However, the main disadvantage of this technology so far has been that the power flow can only be conducted in one direction. This happens since LCC requires the reversal of the DC voltage, while keeping the DC current unchanged, whereas VSC requires the opposite. Consequently, operation needs to be interrupted and the system needs to get de-energized before reversing the power flow [81].

An example multi-terminal network using the hybrid configuration is proposed in [81]. The overview of the proposed scheme is provided in Figure 54.

The LCC rectifier controls the DC current, using a PI controller, while the LCC, operating as an inverter, maintains the network DC voltage level. On the other hand, the VSC connected

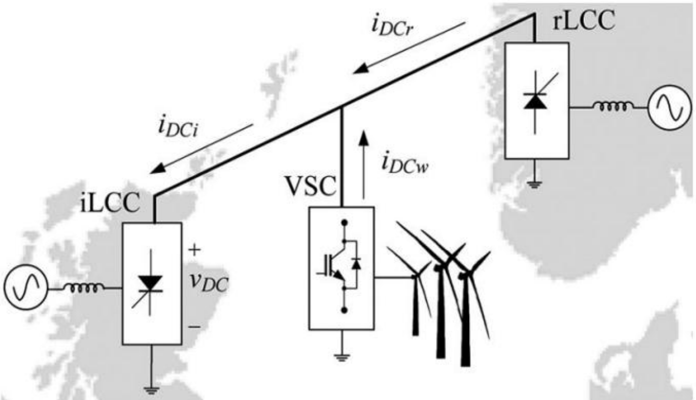


Figure 54: Hybrid MTdc network

at the wind turbine is responsible to support the offshore AC voltage and frequency and mitigate the effects of fluctuating power.

Table 5: Comparison between LCC and VSC-HVdc technologies.

Characteristic	LCC-HVdc	VSC-HVdc
Converter	Line-commutated current-source.	Self-commutated voltage-source.
Switch	Thyristor: turn on capability only.	IGBT: turn-on and turn-off capabilities.
Age	Old: First commercial project in 1954.	New: First commercial project in 1999.
Projects Worldwide	146	15
Power Rating	up to 8000 MW	up to 1000 MW
Voltage Rating	up to ± 800 kV	up to ± 320 kV
Filters	Harmonic orders are high (e.g. 11-th and 13-th), hence high filtering efforts are needed.	Filters are tuned to higher frequencies and are, therefore, smaller and cheaper.
Footprint	Very-high.	Lower.
Control	Always consume reactive power (two-quadrant operation).	Independent control of active and reactive power (four-quadrant operation).
AC Network Requirements	Needs a reasonably strong ac system to operate (high minimum short-circuit ratio, e.g. SCR > 3)	Can operate with an weak ac network or be used to feed islands and passive ac networks providing frequency control. Black start capability.
AC Faults	Presents commutation failure during ac faults. In case of repeated commutation failures the converter is blocked.	Can maintain active power transfer even under ac faults, fault-ride through capable.
DC Faults	Is capable of extinguishing dc-side faults via control actions.	Has no way of limiting dc-fault currents (because of the free-wheeling diodes), therefore dc breakers are needed.
Losses [% of Rated Power]	0.7%	1.5% (two-level) or 1.0% (multi-level)
Communica-tion	Special arrangements are needed to coordinate the operation of converter stations.	Communication between the rectifier station and the inverter station in theory is not necessary. The control of each converter station operates in an independent way.
Multi-terminal Operation	Difficult since there is need for coordination between the converters (current order synchronization) and power-flow reversal involves polarity changes through mechanical switches.	Easier to accomplish since there is little need for coordination between the interconnected converters and power-flow reversal does not involve mechanical switches.

3. Review of technical scenarios

3.1. Introduction

The top consortium for knowledge and innovation Offshore Wind (TKI Wind op Zee) is part of the Dutch government policy to further strengthen high performing industry sectors in the Netherlands through research and development in cooperation with universities and research institutes. The ambitious goals of TKI Wind op Zee are as follows: to reduce by 40% the offshore wind projects cost by 2020 compared to 2010, strengthen the economic activities in offshore wind generation in the Netherlands and support the Dutch offshore wind energy to continue being international leaders in this sector.

Reach the TKI Wind op Zee goals shall contribute significantly to achieve two of the three European Council environmental “20-20-20” targets which are for the Netherlands a 16% greenhouse gas emissions reduction in 2020 comparing it to the 2005 levels and raising the share of energy consumption from renewable resources up to 14% in 2020.

The TKI Wind op Zee wants to realize these challenging goals with research and development (R&D) programs in collaboration with the industry, strategic workflows with projects that serve both the private and public interest, and an offshore wind farm named “project Leeghwater” to test and demonstration of new technologies and methods resulting from the R&D projects.

One of the TKI Wind op Zee projects is the Synergies at Sea (SAS) which seeks to increase energy efficiency and reduce the cost of offshore wind energy by improving the use and capabilities of offshore electricity infrastructure. This includes the infrastructure integration and multiple offshore wind farms interconnection.

The TKI-SAS project runs from January 1st, 2013 and ends in December 31st, 2016 and deepens in technical, legal and financial feasibility aspects. In this project, Grontmij leads the consortium formed by Nuon/Vattenfall, Liandon, ECN, Royal HaskoningDHV, Groningen Centre of Energy Law of the University of Groningen, Delft University of Technology, DC Offshore and Energy Solutions.

The interconnector study is a specific pilot case which is part of the TKI-SAS project. In this pilot case the technology feasibility is assessed of a trans-national connection between United Kingdom (UK) and the Netherlands (NL) via two offshore wind farms planned in each of these countries. This feasibility study presents and discusses different technical scenarios for connecting two offshore wind power plants in the North Sea.

The planned offshore wind farms East Anglia I (UK) and Beaufort (NL) have been selected in this report in order to have a more realistic study. The remainder of this section is organized as follows: first a background about the offshore wind farms and the interconnector used in the scenarios is presented, second a market scenario description is presented which it is the starting point of technical scenarios, third a scenarios description that includes the technical implementation and limitation is introduced, finally a summary of the technical scenarios is submitted.

3.2. Background

The offshore wind energy in the North Sea has the potential to meet a large share of

Europe’s future electricity demand. There are several factors that make the North Sea suitable for large wind generation, among those that stand out are: the first one is the relatively shallow sea because about 40% of its area has a sea depth below 50 m which reduces the offshore wind farm foundation costs, and the second one is the high annual average wind speed that make the wind energy projects development potentially feasible as shown in Fig. 1.

These factors have been a great influence in the growth of offshore wind projects and because of this the North Sea has become the place with the majority offshore wind farms on the world as illustrated in Fig. 3a. Currently, the countries with shore in the North Sea are leaders in offshore wind farm projects as shown in Fig. 3b.

Until now, all offshore wind farms have something in common which is a radial connection to the onshore grid. This means that there is a single connection between each of the offshore power plants and their onshore connection point in whose maritime area the generation occurs. The offshore wind farms have grown in their power ratings, which is achieved by new large wind turbines that are planed far from shore to capture the best wind potentials (see Fig. 1) and ensure space restrictions due to maritime use conflicts.

The increased distance to shore of the new offshore wind projects (see Fig. 5b) have come increasingly to their respective maritime limits. This increase has generated new technological challenges in the transmission of the offshore wind power to the onshore grid in an economic and efficient way.

However, this increased distance has open a new possibility that is the interconnection of different power systems, which allows electricity trade between the countries, through their respectively offshore wind power plants. This kind of transnational interconnection via offshore wind farms has never been built and the interconnection between countries is being done with a direct interconnection as shown in Fig. 55.

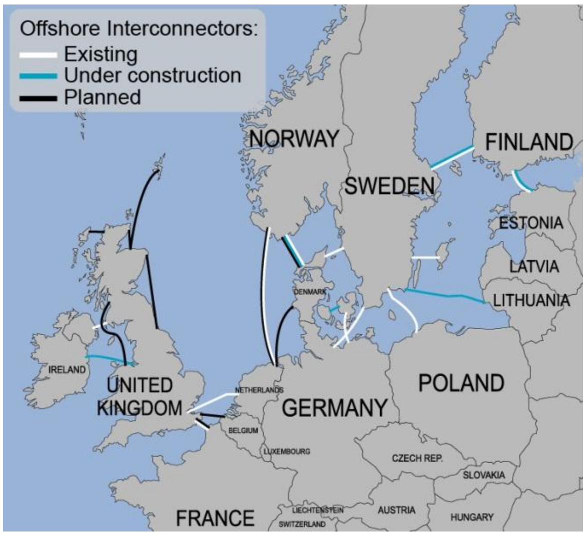


Figure 55: Illustration of a possible offshore grid concept for the North Sea and the Baltic Sea proposed in the OffshoreGrid project.

In the context of our study, the interconnection between the Netherlands and the United Kingdom illustrated in Fig. 55 is the most relevant and it is included in the market and technical scenarios. This interconnector is the BritNed submarine bipolar HVdc cable which has a stretching approximately 260 km from the Isle of Grain in Kent, the United Kingdom; across to Maasvlakte in Rotterdam, the Netherlands as shown in Fig. 56.

The BritNed project was announced in May 2007, the first section of cable was installed on 11 September 2009, the complete cables were installed in October 2010 and it is in operation since April 2011. BritNed ensures greater stability in the European integrated network and it also serve as an energy trading hub because the power can flow in either direction according to the level of supply and demand for electricity in markets which makes them more competitive. A completed technical information about the BritNed HVdc interconnector project can be found in Table 6.

Table 6: Statistics for HVdc interconnector project. Source from [81,82].

Parameter	Characteristics	
Cable data	Power	1000 MW with an overload of 1200 MW for two hours
	Voltage	450 kV DC
	Weight	44 kg/m
	Length sea cable	250 km (two cables, bundled)
	Length land cable	7 km (NL) and 2 km (GB) (two cables, laid together)
	Conductor	1 x 1430 mm^2 MI cable (Cu)
	DC loss factor	3% (across the link)
	Manufacturer	ABB
Cable layout	Burial depth	1 m (as a minimum)
	Water depth	30 m - 50 m
Converter Station	Converter technology	Thyristor
	Thyristor valve	12 pulse converter in double stack configuration
	Substations	Grain (UK) and Maasvlakte (NL)
	AC filter sub-banks	Grain (2 x 225 MVAR + 2 x 160 MVAR) and Maasvlakte (3 x 225 MVAR + 1 x 90 MVAR). Both connected to 400 kV bus bar
	Link between Converter station and substation	Short underground line to 400 kV (UK) Short overhead line to 380 kV (NL)
	Transformers	14 transformers, six transformers plus one spare (reserve) at each AC/DC converter station. There are three 201 MVA single phase transformers for each pole.
	Manufacturer	Siemens / BAM Nuttall consortium

As mentioned previously, the goal of this study is to analyze from a technical aspect the different connection alternatives, which also can include trans-national connection of two planned offshore wind farms in United Kingdom (UK) and the Netherlands (NL). In the UK side, the consortium formed by ScottishPower Renewables and Vattenfall Wind Power have been granted development rights to the zone named East Anglia Zone. The Zone is located 14 km off the coast of Norfolk and Suffolk in the southern North Sea with a cover area of 6000 km^2 approximately and a potential to produce up to 7200 MW through individual offshore windfarm projects, as shown in Fig. 57.

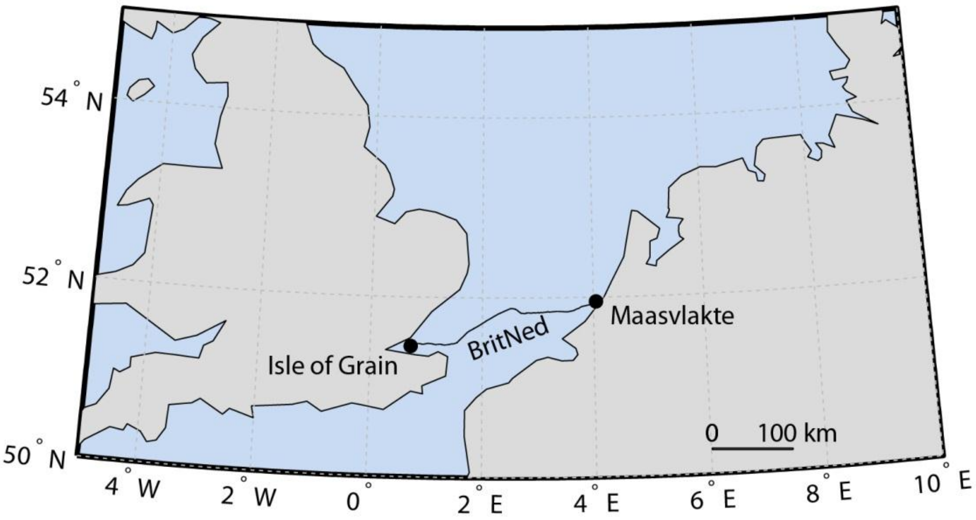


Figure 56: BritNed subsea power cable system. Map coordinates from [12].

This consortium was approved in December 2012 the consent application for both the offshore windfarm and the electricity transmission works of its first project named East Anglia One which is located in the south of the East Anglia Zone. The remaining two wind farm projects, East Anglia three and four situated in the northern half of the East Anglia Zone have been submitted to scoping reports in November 2012. The East Anglia One planned power capacity of 1200 MW generated with up to 325 wind turbines in a approximately cover area of about 300 km^2 has been designed with a grid connection at Bramford, Suffolk. The offshore cable between East Anglia One and the landfall near to Bawdsey is 73 km and the underground cable length from this point to Bramford HVdc substation is 34 km.

On the other hand, on the NL side the offshore wind farm under technical analysis is Beaufort which was formerly named Katwijk. This project has been placed in the Offshore Hollandse kust zone with a power capacity of 279 MW generated with up to 93 wind turbines, as shown in Fig. 58. The Beaufort offshore wind farm is being developed by Nuon and it has been designed with a grid connection at Maasvlakte, Rotterdam. This connection is planned to perform with a 150 kV ac cable and an average length of 35.5 km. A summary of technical information about the East Anglia One and Beaufort offshore wind farm projects can be found in Table 7.

This background sought to explain the technical details concerning the interconnector study which seeks to find the feasibility of creating an interconnection between UK and NL via East Anglia I and Beaufort offshore wind farm projects with the goal to reduce the cost of offshore wind energy. This can be achieved by appropriate electricity infrastructure selection which can ensure an increasing in the utilization, reliability and controllability of the offshore grid infrastructure.

A simple way to understand the benefits of the interconnection between the offshore wind farms described above is presented in Fig. 59. In this figure, while the total length of the BritNed subsea cable is circa 260 km, the trans-national connector depicted in green trace has a length around 100 km with the same power capability. Once explained the general aspects of the different infrastructures presented in Fig. 59 it is time to present in a summary way the market scenarios which are the starting point for the technical scenarios.

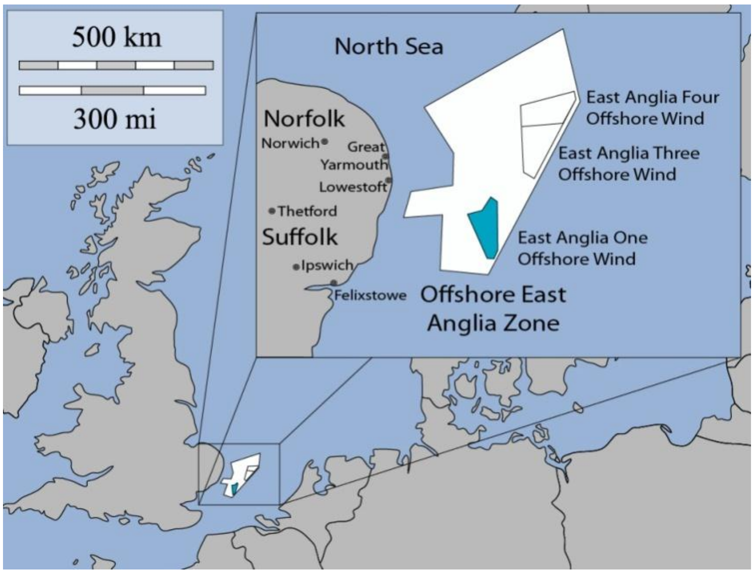


Figure 57: Map of the East Anglia Zone which includes the wind farm projects calling East Anglia one, three and four. Each of them with a planned capacity of 1200 MW.

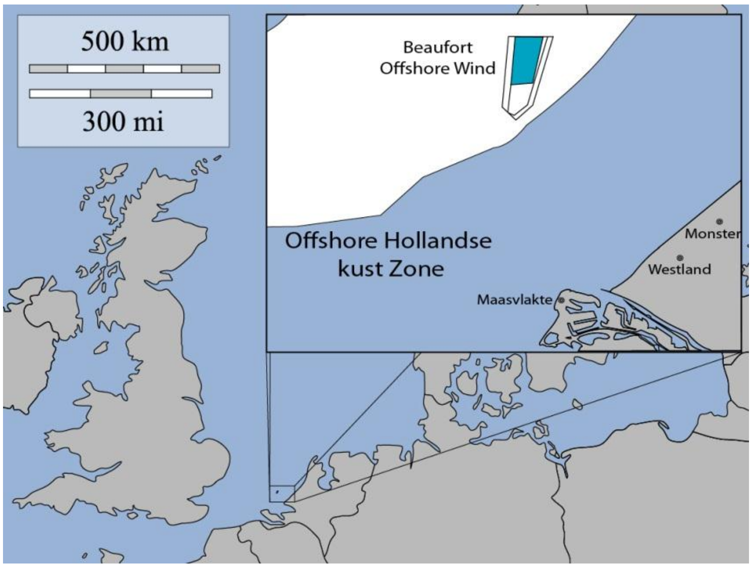


Figure 58: Map of the Offshore Hollandse kust zone which includes the wind farm project calling Beaufort.

3.3. Market scenarios

The market scenarios are based in the trans-national connection between United Kingdom and the Netherlands via two offshore wind farm planned projects, the East Anglia I and Beaufort, and the BritNed cable, as shown in Fig. 59. For the market scenarios a “copper plate”' model has been used. This kind of model is characterized by the absence of an explicit representation of the physical grid model or of the transmission system because only the power flow is relevant. For the offshore grid the “copper plate” model is used, although the resulting losses from the technical simulations will be fed back to the market simulations (leading to extra production costs).

Table 7: Statistics for East Anglia I and Beaufort offshore wind farm projects. Source from 4C offshore wind farms database.

	Information	East Anglia I	Beaufort
General	Country name	United Kingdom	Netherlands
	Region	England, East of England	South Holland
	Other names	East Anglia Array, Zone 5, Norfolk	Formerly Katwijk
Technical	Project Capacity	1200 MW	279 MW
	Turbine Capacity	3 MW – 8 MW	3 MW
	Number of turbines	150-325	93
	Total turbine height	200 m	115 m
	Hub height	120 m	70 m
	Rotor diameter	170 m	90 m
Location	Sea name	North sea	North sea
	Center latitude	52.234°	52.323°
	Center longitude	2.478°	3.975°
	Area	297 km^2	34 km^2
	Distance from shore (reported)	45.4 km	24 km
	Distance from shore (computed from center)	53.8 km	31.2 km
	Grid connection point	Bramford	Maasvlakte

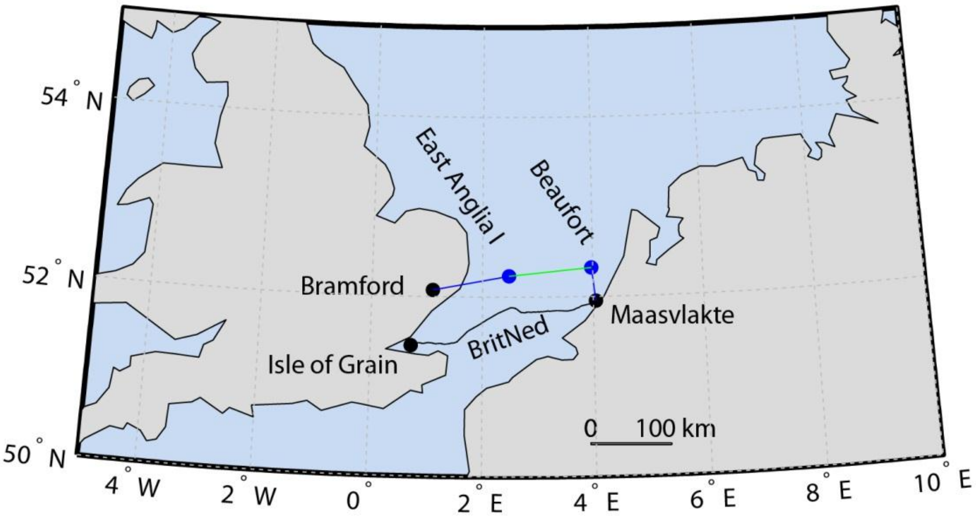


Figure 59: Illustration of a trans-national connection between United Kingdom and the Netherlands via the East Anglia I and Beaufort offshore wind farm planned projects and the BritNed subsea bipolar HVdc cable.

Therefore, the approach for the market scenarios is only to specify the grid topology and the generation and transmission power capacities. Further it is assumed that the power flow in the grid can be controlled as desired, so that the so-called “Net Transfer Capacity” is only determined by the availability of the connections.

All the market scenarios presented in this report have the same two offshore wind farms which are: East Anglia I (UK WF) and Beaufort (NL WF) with an estimated capacity of 1200 MW and 300 MW, respectively. The Beaufort project has a planned power capacity of 279 MW, however this wind farm is still in an early development stage and the final capacity may become larger than the originally planned. The power capacity of 300 MW in the Beaufort project was suggested by Vattenfall. In addition, all the market scenarios have the already constructed BritNed HVdc interconnector cable with a power capacity of 1000 MW which is named in this report “BritNed 1”.

3.3.1. Market scenario 0

The Market scenario 0 corresponds with the case where each wind farm is connected only to its respective country in whose maritime area the generation occurs, as shown in Fig. 60. Only the existing BritNed 1 interconnector, which corresponds with Line 3, is available for cross-border trade.

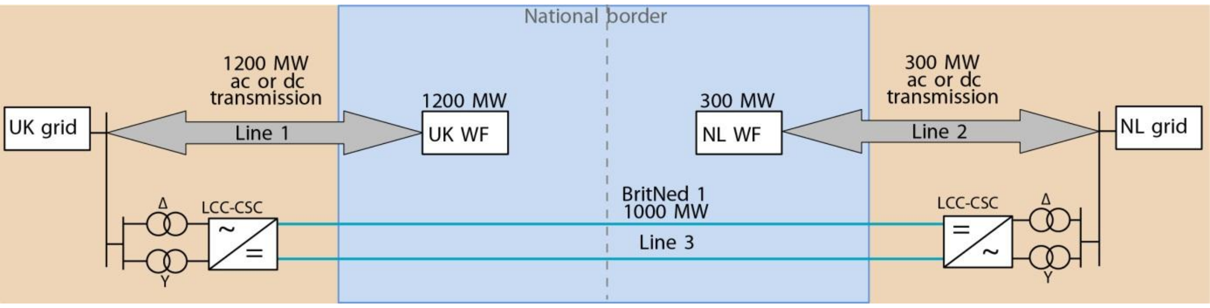


Figure 60: TKI-SaS Market scenario 0.

This scenario corresponds with the original planned projects, that is each wind farm project is connected with its corresponding country and additional trans-national connection different to BritNed 1 is discarded. This scenario could be possible if all the different technical scenarios, which will be presented in this report, are not feasible in either of the legal, technical or economic studies.

In addition, the interconnection between the offshore wind farm and its respectively onshore grid is represented by an arrow because the possibility of an ac or dc transmission is left open, as can be seen in Fig. 60.

In the market scenario 0, the transmission capacity installed in the Lines 1 and 2 are selected to support the nominal wind farm capacity. Market scenario 0 is added, because this scenario is identical to a scenario used in earlier projects, so that this can be used to compare the results. It is important to stand out that the original projects considered an ac transmission technology by Line 1 and dc transmission by Line 2, therefore Market scenario 0 becomes the technical scenario 0 in a practical implementation, as shown in Fig. 61. Note that in this figure the existing interconnector BritNed 1 has been omitted for simplicity.

3.3.2. Market scenario IC

The Market scenario IC corresponds with the case where each wind farm is connected only to its respective country in whose maritime area the generation occurs similar to the market scenario 0. However, the cross-border trade is through the existing BritNed 1 interconnector (Line 3) and a second interconnector named BritNed 2 (Line 4), Fig. 62.

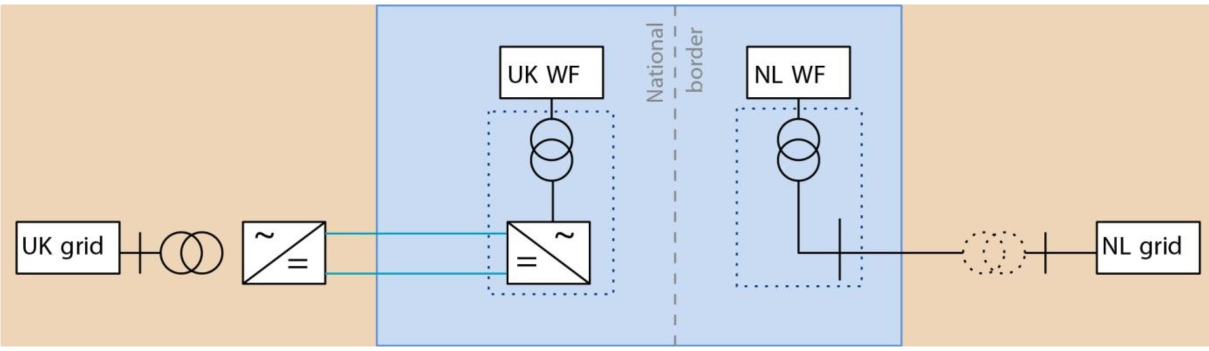


Figure 61: TKI-SaS technical scenario 0.

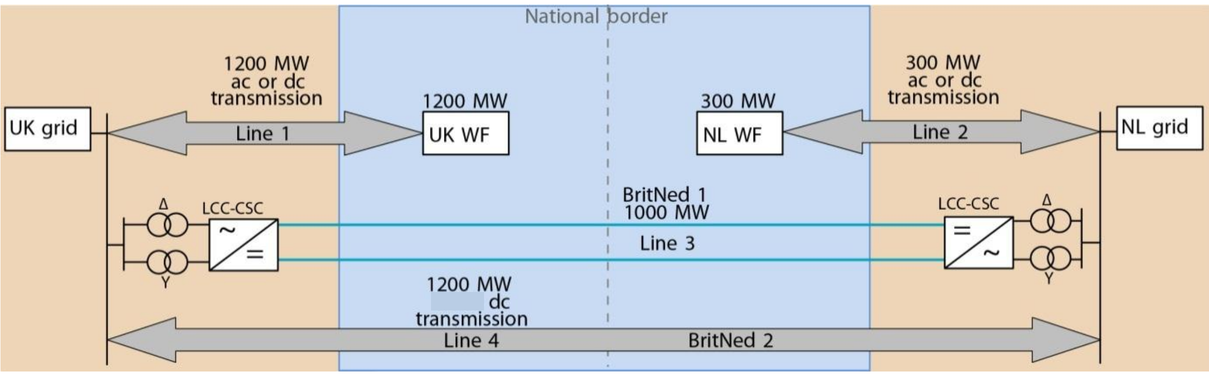


Figure 62: TKI-SaS Market scenario IC1200

The capacity of the BritNed 2 interconnector is assumed of 1200 MW, which correspond with the maximum power capacity of East Anglia I (UK WF). This capacity value is larger than the trading capacities initially chosen for market scenarios UK-NL, UK and NL. Although later on more variants, larger capacities for the trading lines, in these scenarios will be selected. Therefore in a later phase, the market scenario UK-NL, UK and NL could match the trading capacities with the Market scenario Ref.

In this market scenario the transmission capacity installed in the Lines 1 and 2 are selected to support the nominal wind farm capacity, these are 1200 MW and 300 MW, respectively. The interconnection between the offshore wind farm and its respectively onshore grid and also the BritNed 2 interconnector are represented by arrows because the possibility of an ac or dc transmission is left open, as can be seen in Fig. 62.

It is important to stand out that the original projects considered an ac transmission technology by Line 1 and dc transmission by Line 2 and also a HVdc link is chosen for BritNed 2 because it is the most cost effective. Therefore, Market scenario Ref becomes in the technical scenario Ref in a practical implementation, as shown in Fig. 63. Note that in this figure the existing interconnector BritNed 1 has been omitted for simplicity. The tecnical scenario IC is added because this allow to make comparisons between scenarios with an transnational interconnection via the offshore wind turbines in each country, which has never been built, and the classical already explored direct interconnection option (see Fig. 55).

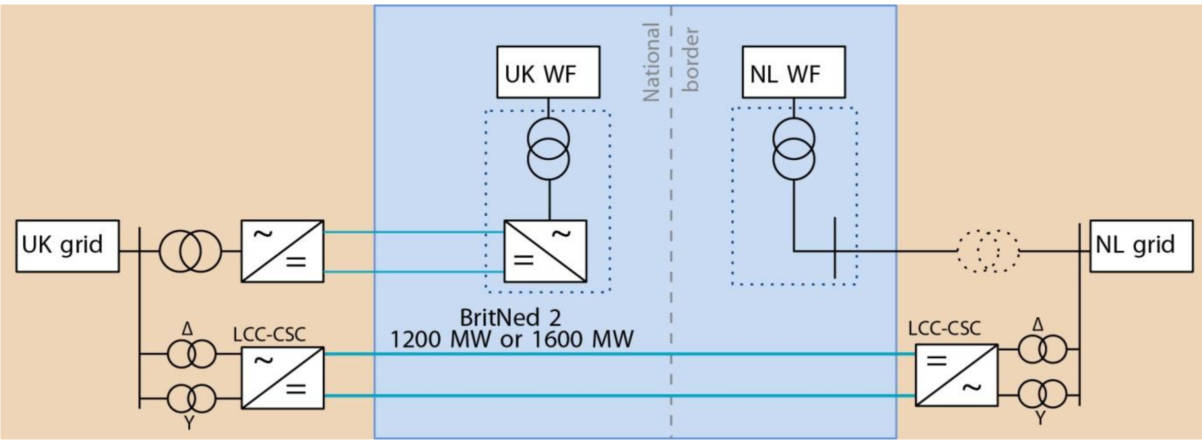


Figure 63: TKI-SaS technical scenario Ref.

3.3.3. Market scenario UK-NL

Until now the market scenarios did not take into account the wind farms interconnection link. The Market scenario UK-NL included an interconnector between the offshore wind farms East Anglia I (UK WF) and Beaufort (NL WF) as shown in Fig. 64. In this market scenario the transmission capacity installed in the Line 1 is selected to support the nominal UK wind farm capacity of 1200 MW. The power capability of the Lines 2 and 5 is selected to support 300 MW in a first phase but with the possibility to extend its power up to 1200 MW in a second phase, as shown in Fig. 64.

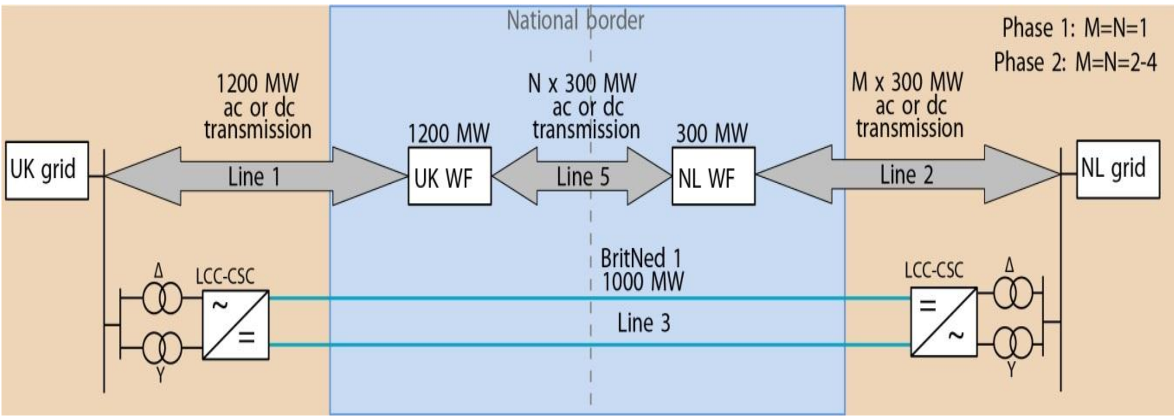


Figure 64: TKI-SaS Market scenario UK-NL.

In this market scenario the transmission capacity installed in the Lines 1, 2 and 5 are represented by arrows because the possibility of an ac or dc transmission is left open. This market scenario may have the same cross-border transport capacity, in a second phase if N=4 (see Fig. 64), that the market scenario Ref in order to facilitate the comparison of the feasibility study results.

However, the trading capacity is in this scenario is not always available, as the case of the Market scenario Ref, because part of the capacity is used for power export from the connected offshore wind farms. This market scenario is studied in six practical implementations in the technical scenarios named Tech-UK-NL where a technical requirements definition and a proper technologies selection is presented in the next section.

3.3.4. Market scenario UK

In addition to Market scenario 0 a so-called interconnecting link between the East Anglia I UK wind farm and the Dutch grid is available, which enables cross-border trade via the UK wind farm export link. In this market scenario the transmission capacity installed in the Lines 1, 2 and 6 are represented by arrows because the possibility of an ac or dc transmission is left open, as shown in Fig. 65.

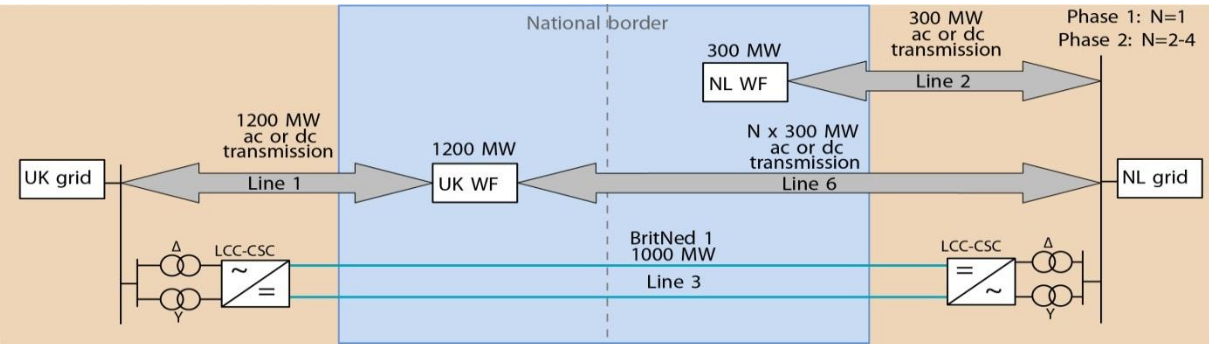


Figure 65: TKI-SaS Market scenario UK.

This market scenario has a transmission capacity installed in the Line 1 to allow transport the planned UK wind farm capacity which corresponds with 1200 MW. In the same way, the transmission capacity installed in the Line 2 corresponds with the Dutch wind farm as can be seen in Fig. 65. Finally, the power capability of the Line 6 is selected to support 300 MW in a first phase but with the possibility to extend its power up to 1200 MW in a second phase, as shown in Fig. 64.

This market scenario may have the same cross-border transport capacity, in a second phase if N=4 (see Fig. 65), that the market scenarios Ref and UK-NL in order to facilitate the comparison of results from the feasibility study. However, this trading capacity is not always available, as the case of the Market scenario Ref, because part of the capacity is used for power export from the UK wind farm. This issue is also present in the Market scenario UK-NL as previously described.

The Market scenario UK is studied in five practical implementations in the Technical scenarios Tech-UK where a technical limitation and challenges are presented in each of the scenarios.

3.3.5. Market scenario NL

The opposite case to the Market scenario UK, is an interconnecting link between the Netherlands wind farm and the UK grid as shown in Fig. 66. This Market scenarios is analyzed in three practical implementations in the Technical scenarios named Tech-NL, where a technical requirements definition and a proper technologies selection is presented.

As it has already been mentioned both offshore wind farms are in a planning stage, therefore the interconnecting link presented in the Market scenarios UK and NL requires the coordination of the connection of two wind farms projects that are often owned and operated by different entities. Therefore, the Market scenarios UK and NL could be seen as the one that explores the possibility that one of the wind farms is not being built.

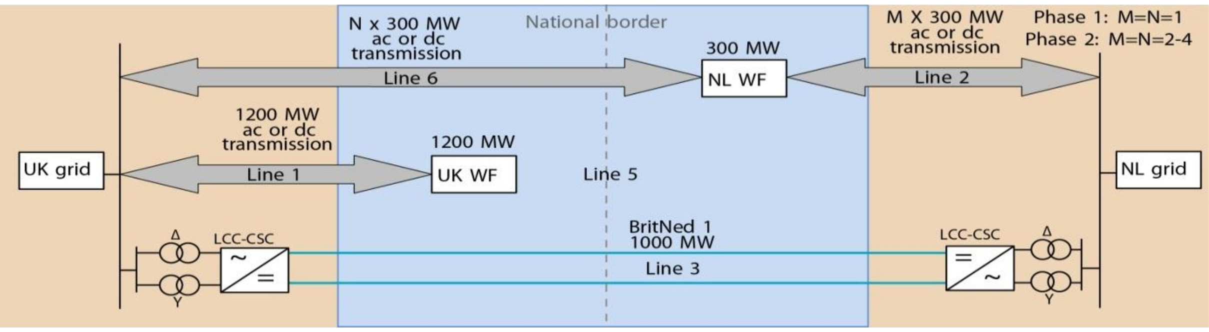


Figure 66: TKI-SaS Market scenario NL.

3.4. Technical scenarios analysis

For the analysis of the different technical scenarios the line lengths are provide in Table 8, all based on the initial choice of a 300MW interconnecting link.

Table 8: Line lengths assumed in the technical scenarios.

From	To	Length offshore [km]	Length onshore [km]
UK WF export cable	UK	73	34
NL WF export cable	NL grid	35.5	0
UK WF export	NL WF export cable	100	0
UK WF export	NL grid	110	0
NL WF export cable	UK grid	173	34

The offshore wind farms power capabilities planned to East Anglia I (UK WF) and Beaufort (NL WF) in this study corresponds to 1200 MW and 279 MW, respectively. At is already been mentioned, the wind farm Beaufort is still in an early development stage and may become larger than the planned capacity. Vattenfall suggested to use a value of 300 MW for this wind farm.

The line capacities of the export lines are chosen identical to the wind farm capacities. The total trading capacity in all the technical scenarios is limited to East Anglia I capacity, which corresponds to a value of 1200 MW. The existing interconnector BritNed 1 has been omitted in all the technical scenarios because it is only included in the market scenarios.

The selection criteria notation used in this report to classify the technical scenarios is presented in Table 9. With red color are grouped the scenarios which are not attractive from a technical point of view, therefore these scenarios are rejected. After 2020 has to do with the application of multi-terminal HVdc networks/converters which are represented in orange color. Finally, in green color are classified the scenarios technically attractive that could be a 2020 Scenario.

Table 9: TKI-SaS Tech scenarios selection criteria notation.

Rejected	After 2020	2020 Scenario
		

The technical scenarios described in the following sections have common technical problems and challenges. In order to simplify the scenarios analysis, the main issues will be briefly explained below. A more detailed explanation of each of them is provided in the Section 2.3.

- **AC cable reactive power compensation**: The active power transmission through ac cable is limited by the reactive power in the long ac transmission cable. This problem is compounded in the case of submarine ac cable because this kind of cable produces large amounts of capacitive reactive power. In the case of submarine ac cable the transmission capability decreases sharply as a function of distance (see Fig. 32), therefore large reactive power compensation are required in certain scenarios. In addition, the reactive power compensation increases the transmission system costs. The ac cable reactive power compensation are grouped into five categories: low, medium–low, medium, medium–high, and high reactive power requirements. These categories are designated according to calculations based on the information given by the manufacturers in their data sheets.

- **Hybrid CSC/VSC connection**: A CSC station could be LCC or Forced Commutation (FC). LCC is a mature technology that is presented in most of the HVdc systems in operation nowadays. The CSC-FC as a dual topology to use dos not exist yet and it is a challenge from the converter technology and VSC-CSC connection view of point. By assuming CSC-FC in all the topologies with LCC a new characteristics and performance will be obtained. Nevertheless, the CSC-FC technology will not be available before 2020. On the other hand, the main disadvantage of a hybrid LCC/VSC connection is that the power can only flow in one direction. This happens since LCC requires the reversal of the DC voltage, while keeping the DC current unchanged, whereas VSC requires the opposite. Consequently, the operation needs to be interrupted and the system needs to get de-energised before reversing the power. This is a great drawback because in the interconnecting link presented in the technical scenarios the power can flow in either direction according to the level of supply and demand for electricity in Dutch and UK markets. Another drawback is that the LCC technology reaches power ratings up to 8000 MW while the VSC stations currently have values of circa 2000 MW to [84]. Therefore, the combining of both converter technologies limits the power rating in the LCC station. A comparison of both technologies is listed in Table 5.

- **Multi-terminal dc network**: The operation of a LCC converter in a multi-terminal dc network is difficult due to: power-flow reversal involves polarity changes through mechanical switches and the coordination between the converters (see Table 5). On the other hand, the high controllability of the VSC technology facilitates large multi-terminal networks. However, the multi-terminal dc network based on VSC technology represents a challenge since the breakers are not available and the control system needs to be developed.

- **Component is not available**: In some cases, a technical scenario could be not technically feasible because a specific component is currently not available. This may happens when a component does not have a specific required electrical parameter (power, voltage, ampere, among many others) or the component just does not exist at the present time.

- **LCC reactive power compensation**: A LCC station consumes reactive power, hence this station requires a strong ac network and capacitor banks capable of providing the necessary reactive power for its operation. Furthermore, LCC stations have a very high-footprint which makes it impractical for offshore applications. Hence, the above conditions restrict the converters in the technical scenarios which can be a LCC station.

In addition, there are factors with high influence on the total project cost of each technical scenario such as:

- **Number of converters**: The synchronously connection of different power systems are part of what is known as synchronously connected area which is characterized to have the same frequency in all the connected electric power system. Six regional synchronous zones have emerged in Europe from the power system operators co-operation as shown in Fig. 31. This figure shows that the UK and Dutch power systems are not synchronous, therefore a direct ac connection is not technically feasible. The use of dc technology allows to create an asynchronous interconnection between the ac networks of both countries, even though the expensive HVdc converter costs that are required to interface between the ac and dc system.

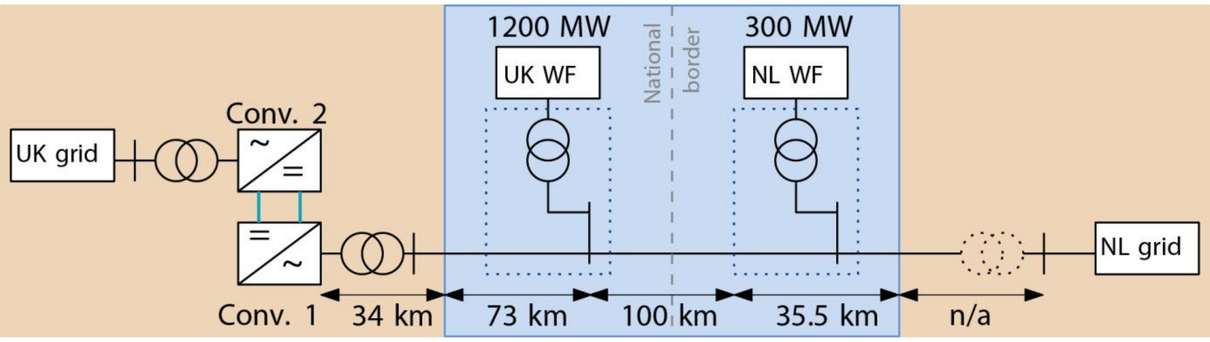
- **Cost estimation**: According with the possible issues listed up here, it is possible to make a cost estimation with five possible values which are noted with the symbol €. The number of Euro symbols is only indicative for the cost. Therefore, in the technical scenarios the highest cost estimation is represented by €€€€€ while the lowest cost estimation corresponds with €. The cost estimation depends on several factors such as: amounts of reactive power compensation in the submarine ac cables and/or in the LCC stations, the number of HVdc converters in each scenario and if they are placed onshore or offshore, the dc and/or ac cables length, the sub-stations power capability, the technology available, and so on. The cost estimation is based on the most recent manufacturers database.

In the technical scenarios analysis presented below will be referenced the technical problems and challenges, and the economic factors described above.

3.4.1. Technical scenario Tech-UK-NL-a

Description

This scenario consists in the trans-national interconnection link between UK WF and NL WF with a 100 km of submarine ac cable. The same ac transmission technology has been used in this scenario to connect the wind farms to the nearest onshore grid, that is 107 km in the UK side (34 km onshore and 73 km offshore) and 35.5 km in the Dutch side. Therefore, the total ac cable has a length of 242.5 km from both onshore grids. A back-to-back onshore station in the UK side is used to create an asynchronous interconnection between Uk and NL grid networks.



Technical limitations

AC cable reactive power compensation:	medium–high amounts (242.5 km of ac cable)
Hybrid LCC/VSC connection:	possible if Conv. 2 is selected as a LCC station.
Multi-terminal dc network:	not present in this scenario.
Component is not available:	all available.
LCC reactive power compensation:	possible if Conv. 2 is selected as a LCC station.
VSC:	available technology.
CSC:	LCC available and CSC-FC is not available.
AC cables:	power transfer limited (see Fig. 32). The ac cables require medium–high reactive power compensation.
DC cables:	no dc cables.
Number of converters:	two converters (both onshore).
Cost estimation:	€€

Preliminary decision

	The long distance between UK and NL grids present high reactive power losses with HVac submarine cable. Moreover, technical limits of HVac would lead to very high costs (and also poor controllability). It could be better to use a dc transmission cable in this scenario.

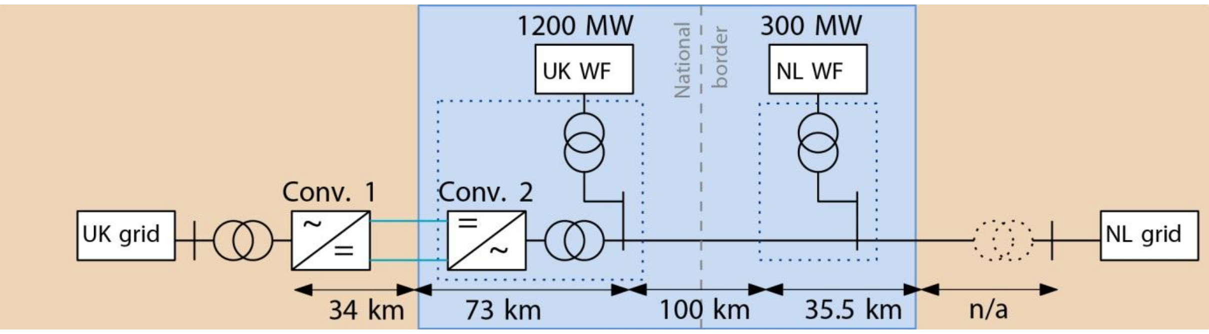
Technical maturity and R&D challenges

The main challenge to make this scenario achievable is the development of new submarine HVac cables with a capacitive reactive power that allows long cables.
The possible hybrid combination of VSC station (Conv. 1) and LCC station (Conv. 2) represents a significant challenge.

3.4.2. Technical scenario Tech-UK-NL-b

Description

This technical scenario consists in an interconnection link between the UK and NL offshore wind farms with a 100 km of submarine ac cable. The same ac transmission technology has been used in this scenario to connect the NL WF offshore wind farm to the Dutch onshore grid, with a length of 35.5 km. Therefore, the total ac cable has a length of 135.5 km from the UK WF export cable across to the Netherlands grid. On the other side, the UK grid is connected to UK WF by means of a HVdc cable. The use of dc transmission system is a naturally alternative because it allows to create an asynchronous interconnection between UK and the Netherlands ac networks.



Technical limitations

AC cable reactive power compensation:	medium–high amounts (135.5 km of ac cable)
Hybrid LCC/VSC connection:	possible if Conv. 1 is selected as a LCC station.
Multi-terminal dc network:	not present in this scenario.
Component is not available:	all available.
LCC reactive power compensation:	possible if Conv. 1 is selected as a LCC station.
VSC:	available technology.
CSC:	LCC available and CSC-FC is not available.
AC cables:	power transfer limited (see Fig. 32). The ac cables require medium reactive power compensation.
DC cables:	dc cables available.
Number of converters:	two converters (one onshore and one offshore).
Cost estimation:	€

Preliminary decision

	The long distance between UK wind farm and NL grid present high reactive power losses with HVac submarine cable. However, this scenario could be a 2020 Scenario because effectively the ac cable is split in two sections (300 MW, 100 km and 300 MW, 35 km) during the first phase which is feasible with the current technology.

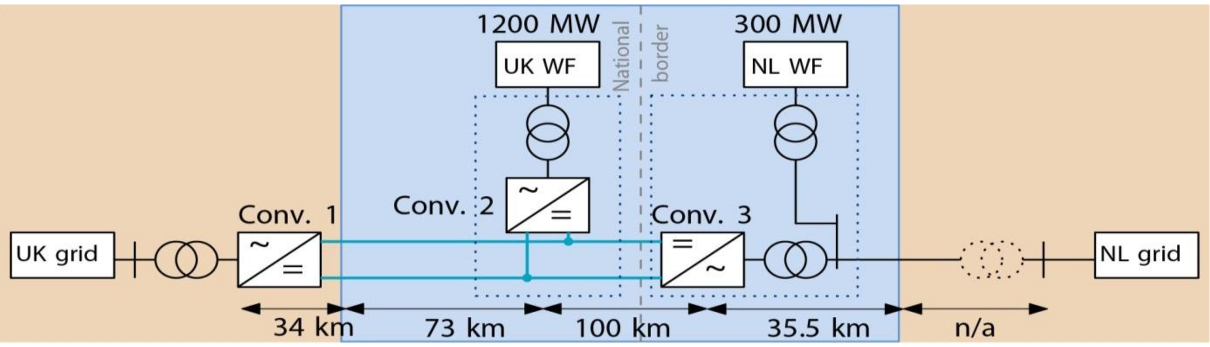
Technical maturity and R&D challenges

The main challenge to make this scenario achievable is the development of new submarine HVac cables with a capacitive reactive power that allows transmitting power over long distances.
The possible hybrid combination of LCC station (Conv. 1) and VSC station (Conv. 2) represents a significant challenge.

3.4.3. Technical scenario Tech-UK-NL-c

Description

The technical scenario Tech-UK-NL-3 consists of a trans-national connection between the offshore NL WF export cable and the UK grid with a 207 km of submarine dc cable, as shown above. An ac transmission technology has been used in this scenario to connect the Dutch offshore wind farm to its onshore grid system, with a length of 35.5 km. The UK wind farm is connected to the trans-national dc transmission system by means of converter 2. The use of a dc transmission system allows to create an asynchronous interconnection between the ac networks of both countries.



Technical limitations

AC cable reactive power compensation:	low amounts (35.5 km of ac cable).
Hybrid LCC/VSC connection:	possible if Conv. 1 is selected as a LCC station.
Multi-terminal dc network:	present in this scenario.
Component is not available:	all available.
LCC reactive power compensation:	possible if Conv. 1 is selected as a LCC station.
VSC:	available technology.
CSC:	LCC available and CSC-FC is not available.
AC cables:	power transfer limited (see Fig. 32). The ac cables require low reactive power compensation.
DC cables:	dc cables available.
Number of converters:	three converters (one onshore, two offshore).
Cost estimation:	€€€€€

Preliminary decision

	Since a multi-terminal HVdc system would be built then it would make more sense if the Dutch terminal is onshore rather than offshore because the distance from wind farm platform to coast is only 35.5 km. From a cost perspective this solution is not attractive due to the additional offshore wind platform for the HVdc converter. However, this scenario is technically attractive and could be studied after 2020.

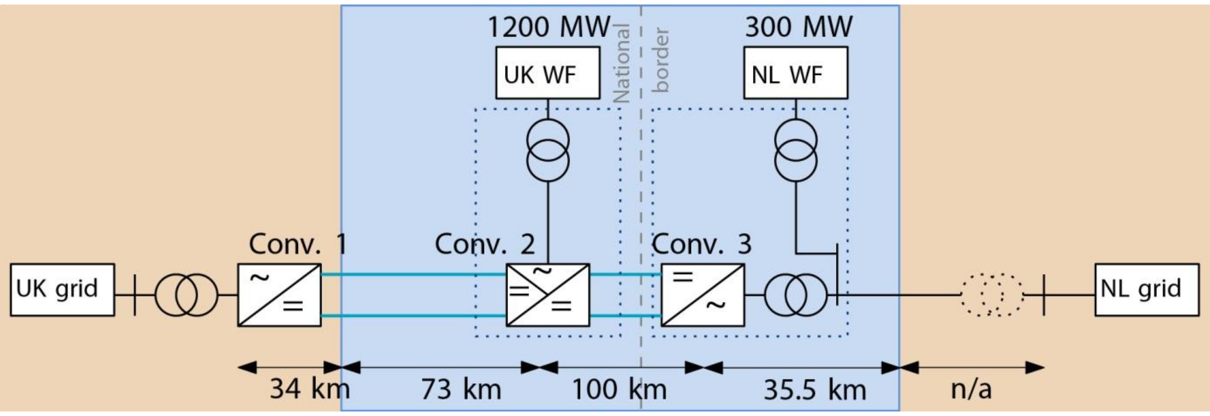
Technical maturity and R&D challenges

The main research challenges in this scenario correspond with the control and the protection of a multi-terminal dc network. Another challenge in this technical scenario is to increase the VSC power capability to allow future interconnections from another dc grids in the UK side.

3.4.4. Technical scenario Tech-UK-NL-d

Description

This technical scenarios consists of a trans-national interconnection link between both offshore wind farms with a 100 km of submarine dc cable. An ac transmission technology has been used in this scenario to connect the Dutch offshore wind farm to the Netherlands onshore grid, with a length of 35.5 km. The UK wind farm is connected to the trans-national dc transmission system by means of converter 2 which is a 3-terminals HVdc converter. The intended purpose is to use 100 km MVdc cable and 300 MW MVdc converter at NL side, because of the lower power rating of the NL-WF.



Technical limitations

AC cable reactive power compensation:	low amounts (35.5 km of ac cable).
Hybrid LCC/VSC connection:	possible if Conv. 1 is selected as a LCC station.
Multi-terminal dc network:	present in this scenario.
Component is not available:	3-terminals HVdc converter is not yet available.
LCC reactive power compensation:	possible if Conv. 1 is selected as a LCC station.
VSC:	available technology.
CSC:	LCC available and CSC-FC is not available.
AC cables:	power transfer limited (see Fig. 32). The ac cables require low reactive power compensation.
DC cables:	dc cables available.
Number of converters:	three converters (one onshore and two offshore).
Cost estimation:	€€€€€

Preliminary decision

	This scenario is not technically feasible at the present because a 3-terminals HVdc converter is not yet available, therefore the scenario is technically attractive and could be studied after 2020.

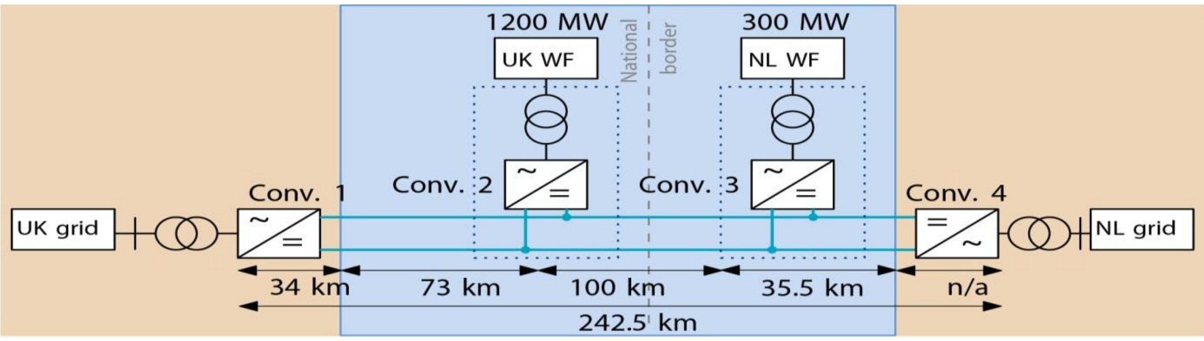
Technical maturity and R&D challenges

A 3-terminals HVdc converter calling ``converter 2'' in the diagram is not yet available, therefore a the multiport-converter could be studied further due to the novelty of this topology and represents a high research challenge in this scenario.

3.4.5. Technical scenario Tech-UK-NL-e

Description

As has been described previously, long submarine ac cables produce large amounts of capacitive reactive power which limits the active power transmission. For this reason, a scenario with a completely dc technology by trans-national interconnection link and the wind farms connection to shore is addressed here. In addition, the dc interconnection allows to create an asynchronous interconnection between UK and the Netherlands ac networks and the cross-border trade via the wind farm export links with 242.5 km of submarine dc cable.



Technical limitations

AC cable reactive power compensation:	no ac cable in this scenario.
Hybrid LCC/VSC connection:	possible if Conv. 1 or 4 are selected as a LCC station.
Multi-terminal dc network:	present in this scenario.
Component is not available:	all available.
LCC reactive power compensation:	possible if Conv. 1 or 4 are selected as a LCC station.
VSC:	available technology.
CSC:	LCC available and CSC-FC is not available.
AC cables:	no ac cable in this scenario.
DC cables:	dc cables available.
Number of converters:	Four converters (two onshore, two offshore).
Cost estimation:	€€€€

Preliminary decision

	This scenario is technically attractive, however the breakers are not available and the control system needs to be developed, therefore this scenario could be studied after 2020.

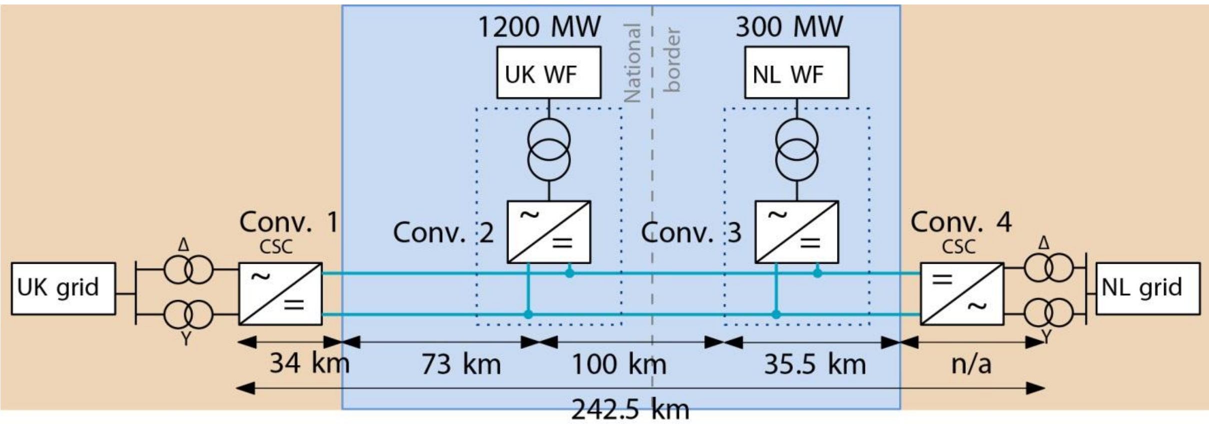
Technical maturity and R&D challenges

The main research challenges in this scenario correspond with the control and the protection of a multi-terminal dc network. The possible hybrid combination of LCC station (Conv. 1 or Conv.4) and VSC stations (Conv. 2 and 3) represents a significant challenge. Another challenge in this technical scenario is to increase the VSC power capability to allow future interconnections from another dc grids.

3.4.6. Technical scenario Tech-UK-NL-f

Description

This technical scenario follows the same approach than the technical scenario Tech-UK-NL-5 presented above. That is to use a dc technology by the trans-national interconnection link between the wind farms and for the connection of them to their respective shore grid. The advantages of using this dc interconnection is that it allows to create an asynchronous interconnection between UK and the Netherlands ac networks and the cross-border trade via the wind farm export links. In this scenario, the converters 1 and 4 are CSC stations while the converter 2 and 3 only can be a VSC stations.



Technical limitations

AC cable reactive power compensation:	no ac cable in this scenario.
Hybrid LCC/VSC connection:	present in this scenario.
Multi-terminal dc network:	present in this scenario.
Component is not available:	all available.
LCC reactive power compensation:	required in both grid connections.
VSC:	available technology.
CSC:	LCC available and CSC-FC is not available.
AC cables:	no ac cable in this scenario.
DC cables:	dc cables available.
Number of converters:	Four converters (two onshore, two offshore).
Cost estimation:	€€€€

Preliminary decision

	This scenario is technically attractive, however the LCC and VSC tapping at high power transfer is under development and could be studied after 2020.

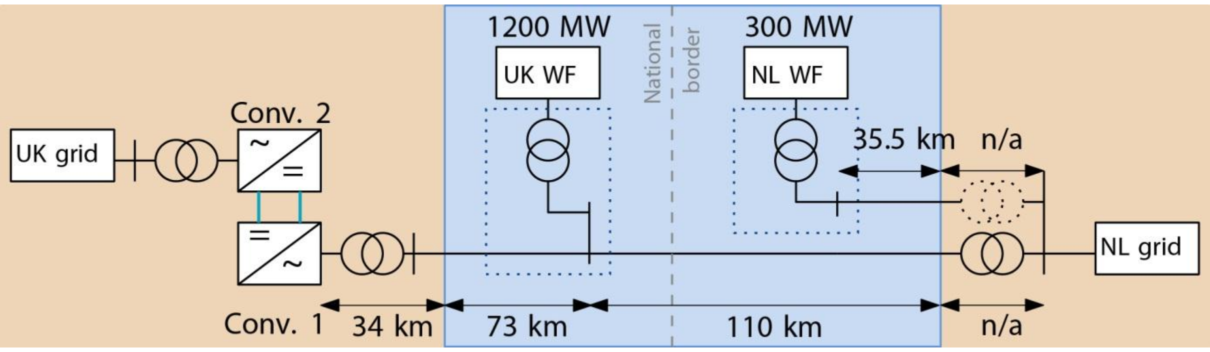
Technical maturity and R&D challenges

The main research challenges in this scenario correspond with the control and the protection of a multi-terminal dc network. The hybrid combination of the onshore LCC stations with the offshore VSC stations represents technical challenges that can be addressed in a future research. The development and application of a FC-CSC converter is another challenge of this scenario. Another research challenge is extend the VSC capabilities to allow high power transfer with the onshore LCC and futures interconnections from another dc grids.

3.4.7. Technical scenario Tech-UK-a

Description

This scenario consists in the trans-national interconnection link between UK WF and the onshore Dutch grid (NL grid) with a 110 km of submarine ac cable. The same ac transmission technology has been used to connect the NL WF to the onshore grid in the Netherlands through of an independently interconnector cable with a length of 35.5 km. The same ac transmission technology has been used in this scenario to connect the UK wind farm to its onshore grid with 107 km of ac cable (34 km onshore and 73 km offshore). Therefore, the total ac cable has a length of 242.5 km from both onshore grids. A back-to-back onshore station in the UK side is used to create an asynchronous interconnection between Uk and NL grid networks.



Technical limitations

AC cable reactive power compensation:	high amounts (242.5 km and 35.5 km of ac cables).
Hybrid LCC/VSC connection:	possible if Conv. 2 is selected as a LCC station.
Multi-terminal dc network:	not present in this scenario.
Component is not available:	all available.
LCC reactive power compensation:	possible if Conv. 2 is selected as a LCC station.
VSC:	available technology.
CSC:	LCC available and CSC-FC is not available.
AC cables:	power transfer limited (see Fig. 32). The ac cables require high reactive power compensation.
DC cables:	no dc cables.
Number of converters:	two converters (both onshore).
Cost estimation:	€€€

Preliminary decision

🔴⚪⚪	This scenario is not technically attractive because has the same UK-NL-1a scenario disadvantages

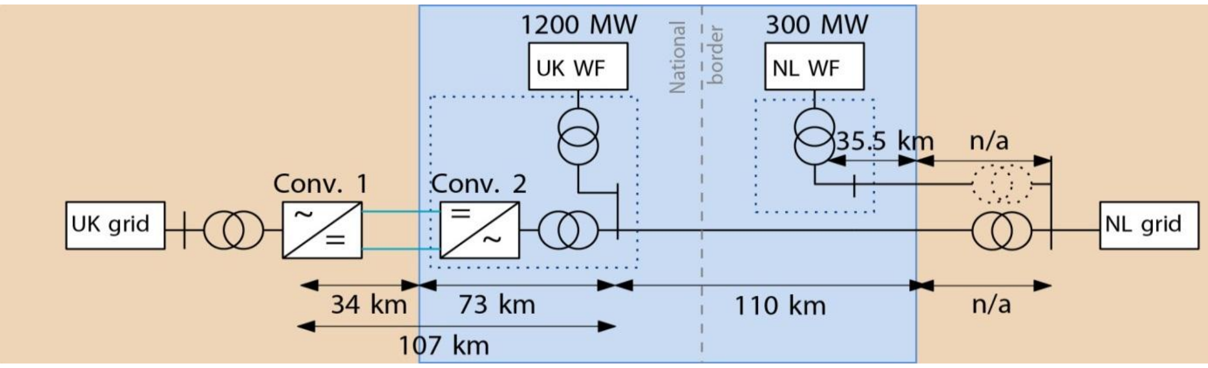
Technical maturity and R&D challenges

The main challenge to make this scenario achievable is the development of new submarine HVac cables with a capacitive reactive power that allows long cables. The possible hybrid combination of VSC station (Conv. 1) and LCC station (Conv. 2) represents a significant challenge.

3.4.8. Technical scenario Tech-UK-b

Description

This scenario consists in the trans-national interconnection link between UK WF and the onshore Dutch grid (NL grid) with a 110 km of submarine ac cable. The same ac transmission technology has been used to connect the NL WF to the onshore grid in the Netherlands through of an independently interconnector cable with a length of 35.5 km. On the other side, the UK grid is connected to its offshore wind farm with 107 km of HVdc cable (34 km onshore and 73 km offshore). The use of dc transmission system is a naturally alternative because it allows to create an asynchronous interconnection between UK and the Netherlands ac networks.



Technical limitations

AC cable reactive power compensation:	high amounts (135.5 km and 35.5 km of ac cables).
Hybrid LCC/VSC connection:	possible if Conv. 1 is selected as a LCC station.
Multi-terminal dc network:	not present in this scenario.
Component is not available:	all available.
LCC reactive power compensation:	possible if Conv. 1 is selected as a LCC station.
VSC:	available technology.
CSC:	LCC available and CSC-FC is not available.
AC cables:	power transfer limited (see Fig. 32). The ac cables require high reactive power compensation.
DC cables:	dc cables available.
Number of converters:	two converters (one onshore and one offshore).
Cost estimation:	€€

Preliminary decision

	This technical scenario is feasible and could be a 2020 Scenario. The distance between the UK WF and the onshore Dutch grid is 110 km and with a power capacity of 300 MW in a first phase. Therefore, this line is possible with the current technology.

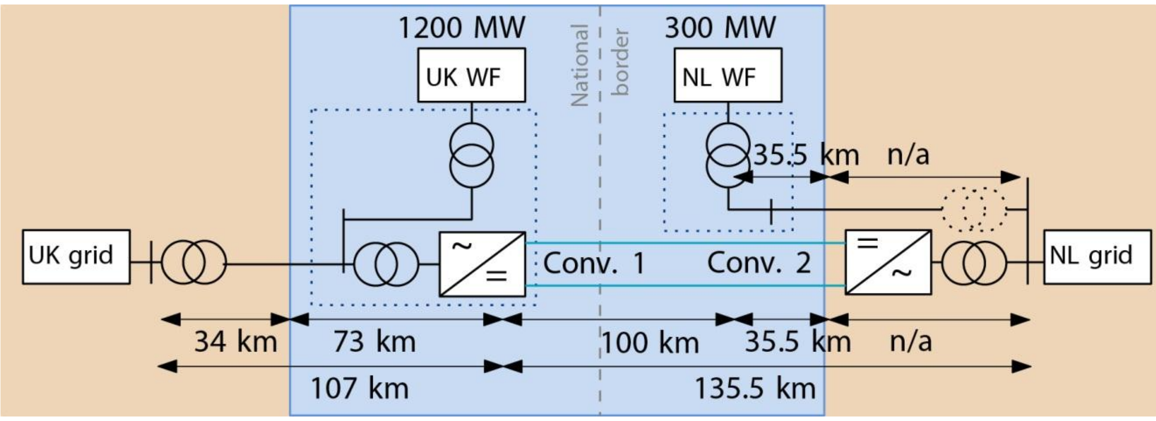
Technical maturity and R&D challenges

The main challenge to make this scenario achievable is the development of new submarine HVac cables with a capacitive reactive power that allows long cables. The possible hybrid combination of VSC station (Conv. 2) and LCC station (Conv. 1) represents a significant challenge.

3.4.9. Technical scenario Tech-UK-c

Description

The technical scenarios Tech-UK-3 consists of a trans-national connection between the offshore UK WF export cable and the Netherlands onshore grid with a 135.5 km of submarine dc cable. An ac transmission technology has been used in this scenario to connect the offshore NL WF to the Dutch onshore grid, with a length of 35.5 km. In addition, the UK WF wind farm is connected to its onshore grid using a submarine ac transmission system.



Technical limitations

AC cable reactive power compensation:	medium amounts (107 km and 35.5 km of ac cables).
Hybrid LCC/VSC connection:	possible if Conv. 2 is selected as a LCC station.
Multi-terminal dc network:	not present in this scenario.
Component is not available:	all available.
LCC reactive power compensation:	possible if Conv. 2 is selected as a LCC station.
VSC:	available technology.
CSC:	LCC available and CSC-FC is not available.
AC cables:	power transfer limited (see Figure 32). The ac cables require medium reactive power compensation.
DC cables:	dc cables available.
Number of converters:	two converters (one onshore and one offshore).
Cost estimation:	€€

Preliminary decision

	The long distance between UK and its grid connection presents high reactive power losses with HVac submarine cable. Therefore, this scenario is not technically attractive and is rejected.

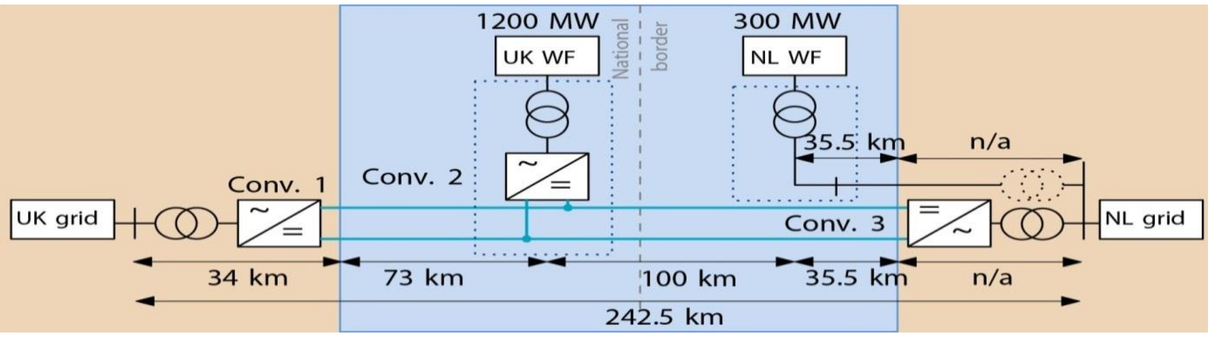
Technical maturity and R&D challenges

The main challenge to make this scenario achievable is the development of new submarine HVac cables with a capacitive reactive power that allows long cables. The possible hybrid combination of VSC station (Conv. 2) and LCC station (Conv. 1) represents a significant challenge.

3.4.10. Technical scenario Tech-UK-d

Description

This technical scenario follows the same approach than the technical scenario Tech-UK-NL-5 presented above. As has been widely described in the previous scenarios, long submarine ac cables produce large amounts of capacitive reactive power which limits the active power transmission. For this reason, a scenario with a completely dc technology by trans-national interconnection link between the onshore grids is addressed here. This technical scenario consists of a trans-national dc interconnection link between UK WF and both onshore grids with 242.5 km of submarine dc cable. UK WF is connected to the trans-national dc transmission system by means of converter 2 while NL WF is connected to the Dutch onshore grid through an ac connector link with a length of 35.5 km.



Technical limitations

AC cable reactive power compensation:	low amounts (35.5 km of ac cable).
Hybrid LCC/VSC connection:	possible if Conv. 1 or 3 are selected as a LCC station.
Multi-terminal dc network:	present in this scenario.
Component is not available:	all available.
LCC reactive power compensation:	possible if Conv. 1 or 3 are selected as a LCC station.
VSC:	available technology.
CSC:	LCC available and CSC-FC is not available.
AC cables:	power transfer limited (see Fig. 32). The ac cables require low reactive power compensation.
DC cables:	dc cables available.
Number of converters:	three converters (two onshore, one offshore).
Cost estimation:	€€€

Preliminary decision

	This scenario is technically attractive, however the breakers are not available and the control system needs to be developed, therefore this scenario could be studied after 2020.

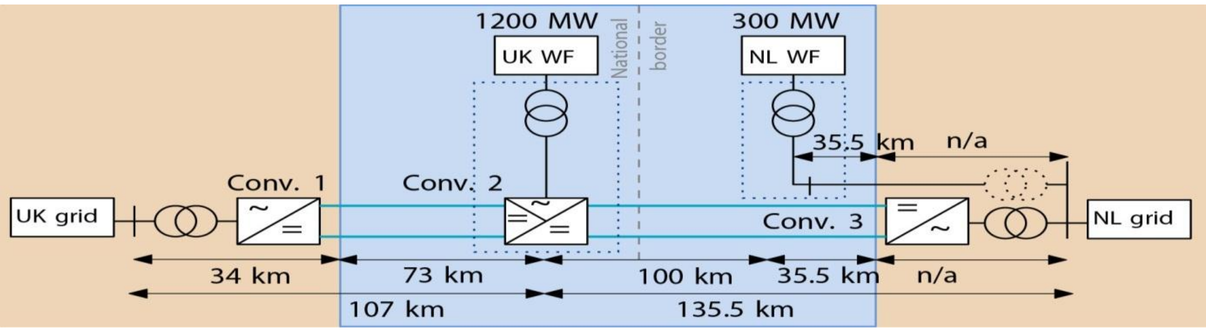
Technical maturity and R&D challenges

The main research challenges in this scenario correspond with the control and the protection of a multi-terminal dc network because the breakers are not available and the control system needs to be developed, as has been previously mentioned in this report.

3.4.11. Technical scenario Tech-UK-e

Description

This technical scenario follows the same approach than the technical scenario Tech-UK-NL-5 presented above. As has been widely described in the previous scenarios, long submarine ac cables produce large amounts of capacitive reactive power which limits the active power transmission. For this reason, a scenario with a completely dc technology by trans-national interconnection link between the onshore grids is addressed here. This technical scenario consists of a trans-national dc interconnection link between UK WF and both onshore grids with 242.5 km of submarine dc cable. UK WF is connected to the trans-national dc transmission system by means of converter 2 while NL WF is connected to the Dutch onshore grid through an ac connector link with a length of 35.5 km.



Technical limitations

AC cable reactive power compensation:	low amounts (35.5 km of ac cable).
Hybrid LCC/VSC connection:	possible if Conv. 1 or 3 are selected as a LCC station.
Multi-terminal dc network:	present in this scenario.
Component is not available:	a 3-terminals HVdc converter is not yet available.
LCC reactive power compensation:	possible if Conv. 1 or 3 are selected as a LCC station.
VSC:	available technology.
CSC:	LCC available and CSC-FC is not available.
AC cables:	power transfer limited (see Fig. 32). The ac cables require low reactive power compensation.
DC cables:	dc cables available.
Number of converters:	three converters (two onshore, one offshore).
Cost estimation:	€€€€€

Preliminary decision

	This scenario has the same UK-NL-d scenario disadvantage. However, this scenario is technically attractive and could be studied after 2020.

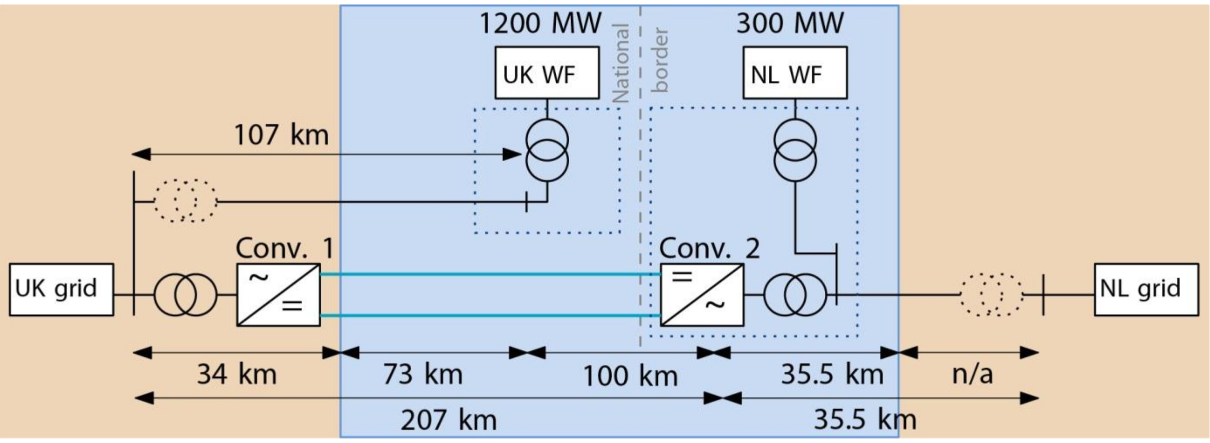
Technical maturity and R&D challenges

A 3-terminals HVdc converter calling “converter 2” in the diagram is not yet available, therefore a the multiport-converter could be studied further due to the novelty of this topology and represents a high research challenge in this scenario.

3.4.12. Technical scenario Tech-NL-a

Description

This technical scenario consists of a trans-national dc interconnection link between NL WF and the UK onshore grid with 207 km of submarine dc cable. In addition, the Dutch wind farm is connected with its corresponding onshore grid by means of 35.5 km of ac cable. Finally, the UK offshore wind farm is connected to its onshore grid through an independent ac connector cable with a length of 107 km.



Technical limitations

AC cable reactive power compensation:	medium amounts (107 km and 35.5 km of ac cables).
Hybrid LCC/VSC connection:	possible if Conv. 1 is selected as a LCC station.
Multi-terminal dc network:	not present in this scenario.
Component is not available:	all available.
LCC reactive power compensation:	possible if Conv. 1 is selected as a LCC station.
VSC:	available technology.
CSC:	LCC available and CSC-FC is not available.
AC cables:	power transfer limited (see Fig. 32). The ac cables require medium reactive power compensation.
DC cables:	dc cables available.
Number of converters:	two converters (one onshore and one offshore).
Cost estimation:	€€€€€

Preliminary decision

	This scenario is technically attractive and could be a 2020 scenario. Economically, this scenario seems less attractive than the reference scenario.

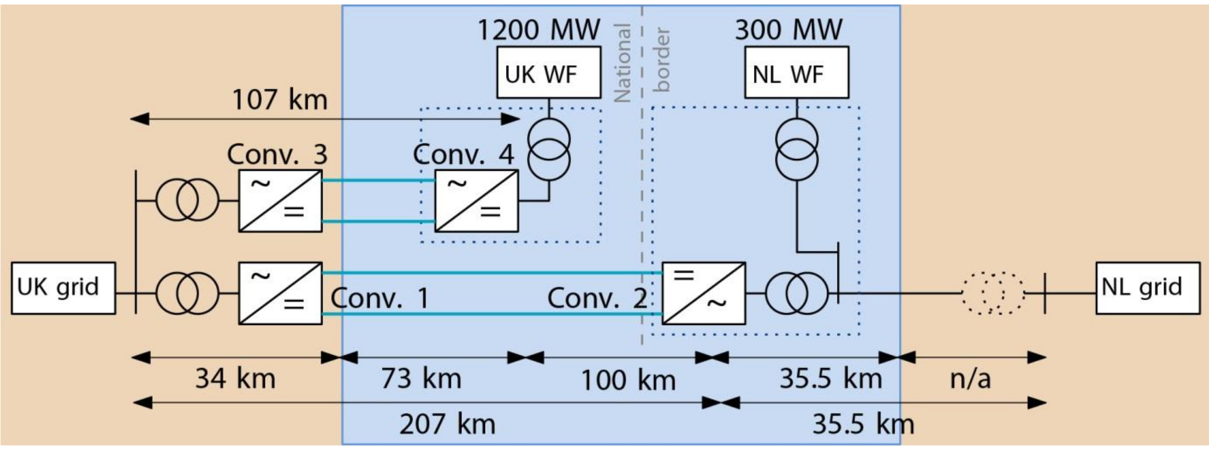
Technical maturity and R&D challenges

The main challenge to make this scenario achievable is the development of new submarine HVac cables with a capacitive reactive power that allows long cables.

3.4.13. Technical scenario Tech-NL-b

Description

This technical scenario consists of a trans-national dc interconnection link between NL WF and the UK onshore grid with 207 km of submarine dc cable. In addition, the Dutch wind farm is connected with its corresponding onshore grid by means of 35.5 km of ac cable. Finally, the UK offshore wind farm is connected to its onshore grid through an independent dc connector cable with a length of 107 km.



Technical limitations

AC cable reactive power compensation:	low amounts (35.5 km of ac cable).
Hybrid LCC/VSC connection:	possible if Conv. 1 or 3 are selected as a LCC station.
Multi-terminal dc network:	not present in this scenario.
Component is not available:	all available.
LCC reactive power compensation:	possible if Conv. 1 or 3 are selected as a LCC station.
VSC:	available technology.
CSC:	LCC available and CSC-FC is not available.
AC cables:	power transfer limited (see Fig. 32). The ac cables require low reactive power compensation.
DC cables:	dc cables available.
Number of converters:	four converters (two onshore and two offshore).
Cost estimation:	€€€€€

Preliminary decision

	This scenario is technically attractive and could be a 2020 scenario. Economically, this scenario seems less attractive than the reference scenario.

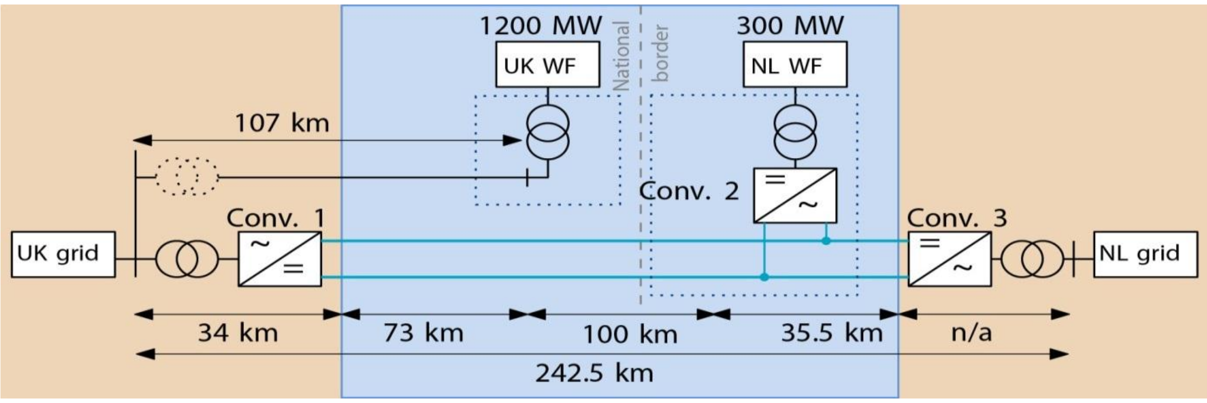
Technical maturity and R&D challenges

The main challenge is the hybrid combination of the onshore LCC stations with the offshore VSC stations. Another research challenge is extend the VSC power transfer capabilities to allow high power transfer with the onshore LCC and futures interconnections from another dc grids.

3.4.14. Technical scenario Tech-NL-c

Description

Long submarine ac cables produce large amounts of capacitive reactive power which limits the active power transmission. Therefore a scenario with completely dc technology transnational interconnection link to the shore grids is addressed here. In addition, the dc interconnection allows to create an asynchronous interconnection between UK and NL ac networks and the cross-border trade via the wind farm export links with 242.5 km of submarine dc cable. The NL wind farm is connected to the trans-national dc transmission system by means of Conv. 2. Finally, the UK offshore wind farm is connected to its onshore grid through an independent ac connector cable with a length of 107 km.



Technical limitations

AC cable reactive power compensation:	medium-low amounts (107 km of ac cable).
Hybrid LCC/VSC connection:	possible if Conv. 1 or 3 are selected as a LCC station.
Multi-terminal dc network:	present in this scenario.
Component is not available:	all available.
LCC reactive power compensation:	possible if Conv. 1 or 3 are selected as a LCC station.
VSC:	available technology.
CSC:	LCC available and CSC-FC is not available.
AC cables:	power transfer limited (see Fig. 32). The ac cables require medium--low reactive power compensation
DC cables:	dc cables available.
Number of converters:	three converters (two onshore, one offshore).
Cost estimation:	€€€€€

Preliminary decision

	This scenario is technically attractive, however the breakers are not available and the control system needs to be developed, therefore this scenario could be studied after 2020.

Table 10: Summary of the Technical scenarios.

Technical scenario	Preliminary decision	Estimated costs	Main R&D challenges
Tech-UK-NL-a		€€	Development new submarine HVac cables with a capacitive reactive power that allows long cables.
Tech-UK-NL-b		€	Development new submarine HVac cables that allows transmission of larger amounts of power to long distances and study the hybrid LCC/VSC connection.
Tech-UK-NL-c		€€€€€	Design the control and protections of the multi-terminal dc network presented in this scenario
Tech-UK-NL-d		€€€€€	Development the 3-terminals HVdc converter required in this scenario.
Tech-UK-NL-e		€€€€	Design the control and protections of the multi-terminal dc network presented in this scenario.
Tech-UK-NL-f		€€€€	Design the control and protections of the multi-terminal dc network presented in this scenario.
Tech-UK-a		€€€	Development new submarine HVac cables with a capacitive reactive power that allows long cables.
Tech-UK-b		€€	Development new submarine HVac cables that allows transmission of larger amounts of power to long distances and study the hybrid LCC/VSC connection.
Tech-UK-c		€€€	Design the control and protections of the multi-terminal dc network presented in this scenario.
Tech-UK-d		€€	Development new submarine HVac cables with a capacitive reactive power that allows long cables.
Tech-UK-e		€€€€€	Development the 3-terminals HVdc converter required in this scenario.
Tech-NL-a		€€€€€	Development new submarine HVac cables that allows transmission of larger amounts of power to long distances.
Tech-NL-b		€€€€€	Study the hybrid LCC/VSC connection.
Tech-NL-c		€€€€€	Development new submarine HVac cables that allows transmission of larger amounts of power to long distances and design the control and protections of the multi-terminal dc network presented in this scenario.

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