TR A7490 - Unrestricted

Report

Technology perspectives of the North Sea Offshore and storage Network (NSON)

Authors
Til Kristian Vrana
Raymundo E. Torres-Olguin

SINTEF Energy Research
Power Conversion and Transmission
2015-08-14

SINTEF Energi AS
SINTEF Energy Research
Address:

NO-
NORWAY

Telephone:+47 73597200
Telefax:+47

energy.research@sintef.no
www.sintef.no/energi
Enterprise /VAT No:
NO 939 350 675 MVA

Report

Technology perspectives of the North Sea Offshore and storage Network (NSON)

VERSION
01

DATE
2015-08-14

AUTHORS
Til Kristian Vrana
Raymundo E. Torres-Olguin

CLIENT(S)
Norges forskningsråd

CLIENT'S REF.

PROJECT NO.
502000391

NUMBER OF PAGES/APPENDICES:
84/4

ABSTRACT

This report contains an overview over the most relevant technologies for realising an offshore power system in the North Sea. Also electric energy storage technologies are being considered, as these may be built offshore and integrated into the offshore power system. Special focus is given on the future perspectives and potentials of the technologies. The technologies are regarded both on component and system level.
This technology assessment is concluded with a gap analysis and recommendations for the ways forward toward the realisation of the North Sea Super Grid.

PREPARED BY
Til Kristian Vrana

SIGNATURE

CHECKED BY
Harald Svendsen

SIGNATURE
Harald G Svendsen

APPROVED BY
Knut Samdal

SIGNATURE
Knut Samdal

REPORT NO.	**ISBN**	**CLASSIFICATION**	**CLASSIFICATION THIS PAGE**
TR A7490	978-82-594-3628-3	Unrestricted	Restricted

Document history

VERSION	DATE	VERSION DESCRIPTION
1	2015-08-14	First version, project deliverable

Table of contents

Executive Summary

Chapter 1: Introduction

The initiative called North Sea Offshore and storage Network (NSON) deals with the development of a future power grid in the North Sea, called the North Sea Super Grid (NSSG). The main drivers for this development are the large number of wind power plants that are to be built in the North Sea far away from shore, and the need for enhanced power transfer capacity across the North Sea.

The NSSG will comprise both AC and DC technologies. AC will be used locally within wind power plants and oil&gas platforms and probably also within offshore clusters which interconnect several of those. Long distance transmission will be DC due to physical limitations of AC transmission. Low frequency AC transmission is a compromise between AC and DC and could be used for both. This has however not often been considered, and most focus lays presently on combined DC+AC solutions.

There are two main possibilities for the topology of the NSSG:

- a true meshed HVDC grid
- a conglomeration of smaller HVDC systems

The first option would possibly be better and cheaper, but it would require an advanced protection and control system to ensure reliability, which could outweigh the advantages. Additionally it would need extensive international coordination of all involved North Sea countries. The second option would rely on proven technology, avoid the need for advanced DC protection systems, and it also would require significantly less coordination.

At the moment, the second option is the realistic one, but the first could become possible in the future. A combination of both concepts is also possible. This will typically be the case, when there is a gradual shift from the second option towards the first option due to technology progress. Since it will take decades to construct a full-scale NSSG, it is likely that different technical solutions will be chosen in the beginning and the end.

Chapter 2: Offshore Network Components

AC-DC conversion will be done with High Voltage Direct Current (HVDC) converter stations based on Voltage Source Converter (VSC) technology. The latest generation of VSC HVDC converters is subdivided in two concepts:

- Modular Multilevel Converter (MMC)
  - based on a large number of small modules
  - introduced by Siemens
  - also available from Alstom Grid
- Cascaded Two Level (CTL) Converter
  - similar concept as the MMC
  - based on larger modules and consequently fewer of them
  - offered by ABB

Other types of VSCs (two-level, three-level, etc.) seem to have disappeared from the HVDC-market, as the most relevant manufacturers have decided to focus on offering the two mentioned converter technologies MMC and CTL. However, there are already existing two-level converters in the North Sea region, which someday might be integrated into the NSSG.

Current Source Converters (CSC), which have been used in the majority of all HVDC projects, will be difficult to integrate into the NSSG. This is due to their large footprint which is problematic offshore, and also due to their operational properties, which do not fit well into the operational concepts of a HVDC grid.

The subsea cables will most likely be based on extruded Cross-Linked PolyEthylene (XLPE) insulation material. This cable type offers significant advantages over Mass Impregnated (MI) cables, but traditionally suffered a severe disadvantage regarding achievable voltage, current and power ratings. In August 2014, ABB released a new XLPE-cable with a voltage rating of 525 kV, and a current rating of 2,5 kA. If this new cable type can prove reliability, and if it can be mass-produced, it has the potential to put XLPE in position as the preferred cable technology of the future.

Energy storage is often considered to be essential in the future power system, to cope with large shares of variable generation facilities like wind and solar. It appears intuitive to consider the implementation of offshore storage facilities, to directly integrate with the offshore wind power plants. The combination of both could act as a smooth and reliable power source, significantly reducing the needs for transmission infrastructure.

Infrastructure is generally more expensive offshore than onshore, posing an economic problem for the realisation of offshore storage. There exist however specific offshore storage concepts based on hydrostatic pressure, which should be taken into account. Examples are pumped hydro and compressed air energy storage.

Chapter 3: Offshore Network System Aspects

A main challenge for the implementation of the NSSG is standardisation.

On the one hand, standardisation is highly needed for realising such a grid. This is not only to bring down cost by competition; it is unrealistic to order such a large project as the NSSG from a single supplier. Also the maintainability for many decades to come cannot be guaranteed when relying on a vendor-specific solution.

On the other hand, standardisation is very challenging regarding new technologies that see fast developments. Many of the relevant technologies have seen fast changes in the last years, and there is little reason to believe that the present solution will be the final one. Over-standardisation today could sabotage future technological progress.

The DC voltage level is possibly the most important standard for a HVDC grid. The new 525 kV cable from ABB has the potential to set a standard for DC voltage level because:

- The voltage level is satisfactory for many future applications
- A higher achievable voltage level for XLPE is not foreseen in the near future
- Mass impregnated cables can (at the moment) not go much higher in voltage (600 kV)

However, there are many more aspects that need standardisation, especially system-wide secondary infrastructure systems like protection, control and communication. Also AC frequency is a matter of standardisation, as both 50 Hz and 60 Hz are applied offshore in the North Sea. This poses an additional challenge for clustering of offshore AC installations. Finally, also a standardisation of support schemes for offshore wind power would be highly beneficial for the technical operation of the NSSG. Non-harmonised support schemes create an incentive for establishing sub-optimal power flow patterns.

Chapter 4: Conclusions

For the development of the future NSSG, the research community needs to address the remaining knowledge gaps:

- Subsea installations
- Hybrid AC+DC grid control
- DC protection systems
- Low frequency AC transmission
- Isolated offshore AC systems
- Value of offshore electric energy storage

The HVDC manufacturers need to continue to invest in technology development, especially with focus on the technology gaps:

- DC fault current limiters
- DC circuit breakers
- High power DC-DC converters
- Offshore storage technology
- Offshore platforms and foundations

Of course, a strong collaboration between the research community and manufacturers is beneficial for all of the mentioned areas of research & development and standardisation. However, to make the manufacturers accelerate their technical development, it is crucial that they receive interest from the TSOs and offshore wind power plant developers, who will be the future customers of the new technologies.

The TSOs have made a lot of progress with regards to offshore HVDC. However, the TSOs still have a lot to go forward regarding multi-terminal HVDC, if we want to see the North Sea Super Grid happening. It would be good to first gain experience with multi-terminal HVDC systems onshore before taking it offshore. Until now not much has happened with multi-terminal HVDC in Europe, where as in China two multi-terminal schemes are in operation. It is highly important that the TSOs and offshore wind power plant developers get involved in the two major demonstration projects that are still missing:

- Medium-voltage DC wind power plant collection system
- Multi-terminal HVDC system

As the TSOs and offshore wind power plant developers at present do not take the extra risks and cost of implementing these, progress could be achieved with a stronger involvement from the governments at national and European level. To move forward, more targeted support for multi-terminal DC technology is needed. Support should focus on realistic intermediate targets like the two proposed demonstration projects, instead of calling for a full-scale meshed offshore super grid from scratch.

1. Introduction

In this century, the main global challenge of the electric power industry is to meet the growing electric energy demand and at the same time focussing on sustainability. Power generation based on sustainable sources can help to accommodate much of the energy demand and minimize the environmental impact in Europe and elsewhere. However, the integration of sustainable power generation implies new challenging issues for the electricity grid such as the variability of the power output.

The initiative called North Sea Offshore and storage Network (NSON) deals with the development of a future power grid in the North Sea, called the North Sea Super Grid (NSSG). The main driver for this development is the large number of wind power plants that are to be built in the North Sea far away from shore. The NSON initiative incorporates several ongoing projects and activities.

One specific activity was to assess the state of the technologies, which are needed to build the NSSG, and to estimate their future prospects. Based on this technology review, the gaps regarding knowledge, technology and experience have been identified and a way forward to close the gaps has been proposed. The technology review, the gap analysis and the proposed ways forward are the main objective of this report.

There exist several reports published, which cover a variety of aspects of offshore grid technologies. However, all of them have a main objective which is substantially different than the main objective of this report. Some published reports, which are in this context relevant, are named here:

- The CIGRE report [1] is addressing HVDC grids in general
    - Offshore aspects are not in focus
- The FOSG report [2] is treating supergrids including both AC and DC based solutions
    - Offshore aspects are not in focus
- The OffshoreGrid report [3] is addressing cost and benefits of offshore grid infrastructure
    - Technical aspects are not in focus
- The NSCOGI report [4] is comparing various offshore grid topologies on economic basis
    - Technical aspects are not in focus
- The ENTSO-E report [5] is addressing subsea transmission technology
    - Offshore installations and multi-terminal grids are not in focus

1.1. Motivation

The fluctuating nature of some sustainable resources (most prominently wind and solar) calls for power supply solutions when the sun is not shining and the wind not blowing. An often discussed solution to this problem is the implementation of large scale energy storage. If energy storage is combined with the fluctuating production facilities, power output fluctuations are reduced, and the combined production/storage area appears as a non-fluctuating power source to the grid. Due to the large number of offshore wind power plants planned in the North Sea, also offshore electricity storage is considered.

Even though a combined sustainable power production and energy storage facility can serve as a reliable power source, it is not always possible/economically efficient to build production and storage co-located. Norway as an example has very large energy storage facilities with its hydropower reservoirs, which cannot be built where needed but only where the landscape allows it. Building storage at the most suitable location rather than production co-located is leading to fluctuating power flows between production and storage facility.

It is also in most cases not economically efficient to utilise a storage facility only to respond to fluctuations of a production facility, ignoring power demand fluctuations. A more sophisticated storage operation concept also leads to more power flow fluctuations between generation, load and storage.

Additionally, it has often been calculated, and it is also intuitive, that it is not cost-efficient to handle all fluctuations of sustainable power sources by storage only. Correlation between different sustainable power sources decreases with geographical distance, leading to significant cancellation effects of the fluctuations, when looking at larger regions. This is partly based on the random characteristics of the weather (if there are strong winds in Norway, it says very little about the winds in Spain). It is also partly based on clearly defined characteristics (solar production peak in Italy happens earlier than in Portugal). The combination of these different effects shows, that 'sustainable energy' in Europe is much less fluctuating than the power output of a single solar cell. To make this consideration of the larger region valid, there needs to be sufficient electric power exchange capacity within the region.

Moreover, sustainable resources are often located far from the load centres, because wind and sunshine cannot be transported to where the electricity consumers are, like it is done with transporting fossil and nuclear fuel. Sustainable energy has to be produced at the location of the resource, leading also to increased power flows. This is especially true for offshore wind power plants in the North Sea, a place with almost no electric loads.

The only relevant electric loads in the North Sea are oil&gas platforms, which have very high security of supply requirements. Traditionally power was generated by gas turbines on the platform, but this gives high carbon dioxide emissions. Electric power transfer from shore is in Norway promoted as the better power supply solution for new platforms, calling for new power transmission infrastructure between shore and platform.

There are significant efforts being done towards implementing a common European electric energy market. The well-known principles of a free market are believed to provide the most economic resource allocation, leading to overall cheaper and more efficient electricity production. This is not only true for the production of electric energy, but also for power balancing services, which also can be allocated using market mechanisms. These markets can however only work properly if transmission capacity within the market area is sufficient that electric power can be transferred between the market actors.

All of the above mentioned arguments call for more electric power transmission infrastructure. The sum of them leads to the inevitable need for massive power grid upgrading. Many people even argue that usual grid expansion approaches will not be sufficient to meet the demands, calling for the so-called European Super Grid to boost the long distance power transmission capabilities.

The transmission capacities are often rather strong within countries, but the international cross-border connections are not always sufficient. This is especially relevant for the North Sea region, which has three non-synchronous power grids (UK, Nordic, Continental), which have not been interconnected synchronously due to the sea in between. The North Sea region has a high need for new transmission infrastructure. This could either be addressed with the usual grid expansion approach meaning the construction of interconnectors between the three grids around the North Sea. Or it could be addressed with the European Super Grid approach, leading to the so called- North Sea Super Grid. The super grid approach is treated in this report.

Even though long distance power transmission can contribute significantly in coping with sustainable power fluctuations, it cannot fully replace energy storage in a future scenario where the power supply of Europe is largely based on fluctuating resources. A better solution can be achieved when combining increased power transmission with energy storage. This is the main subject of interest for the North Sea Offshore and Storage Network initiative.

1.2. Technology in Focus

Will the North Sea Super Grid be AC or DC? That is a good question, where no simple answer is available. A hybrid solution containing both AC and DC components is the most likely outcome, where most long distance transmission is implemented in DC, while most local offshore grids are implemented in AC. The reasoning behind this selection is given later in this section. However, technology pilot projects with other technology implementations are likely to be implemented as well.

1.2.1. Technology for Long Distance Transmission

There are two main alternatives for large scale electric power transmission: high-voltage alternating current (HVAC) and high-voltage direct current (HVDC). HVAC has been the most common electric power transmission technology for more than 100 years. HVDC is dominant concerning long-distance bulk-power transmission, particularly when submarine cables are used.

Regular AC Transmission

Long power cables have a high capacitance, which results in high shunt susceptance at 50 Hz (even higher at 60 Hz), so there is a capacitive current in addition to the active current. This capacitive current utilizes a part of the total current delivery capability. Therefore, long HVAC cables produce excessive amounts of reactive power which in the end reduce the total active power transfer capability. This reactive power can be absorbed by using reactive shunt compensation, but this is at the expense of the investment and operating costs [6]. For long cables, mid-point compensation might be required in addition to compensation at the cable ends. Mid-point compensation is challenging in an offshore system.

Low Frequency AC Transmission

Low frequency AC (LFAC) transmission has been proposed to improve the transmission capacity of HVAC systems. Basically, a LFAC system is an AC system which is operated at a frequency lower than the standard grid frequency. The frequency usually considered for LFAC is a third of the standard grid frequency (16,7 Hz). This frequency is used in several European railway systems. It can be seen as a compromise between regular AC transmission (50 Hz) and DC transmission (0 Hz).

Susceptance has a linear relationship to both capacitance and frequency, leading to a reduction of the susceptance to a third compared to 50 Hz. This indicates that the achievable transmission distance is about three times longer compared to regular AC transmission.

Network components for LFAC transmission can be designed in a similar way as known for regular AC transmission. They can therefore be based on well-known principles, reducing development cost and risk compared to newly developed DC components. One of the main challenges is the size of the transformers which have to be designed for a three times higher magnetic flux, resulting (by rule of thumb) in a three times bigger and heavier magnetic core compared to a normal 50 Hz transformer.

DC Transmission

For DC at 0 Hz this capacitive susceptance phenomenon disappears. The capacitive current only charges the cable once at start-up, so shunt reactive compensation is not needed. For HVDC the transmission distance is therefore only limited by the conduction losses of the cable [7]. It is therefore able to overcome the above-mentioned limitations of HVAC transmission for long-distance transmission. So, for cable applications (offshore), HVDC becomes a more attractive solution in terms of investment and operating costs as the distance from the shore increases.

Transmission power losses are lower for HVDC than HVAC. However, AC-DC and DC-AC conversion, required for integrating HVDC into existing AC systems, creates additional losses. These are not transmission distance dependent, so for long distances HVDC can achieve the lower total losses [7]. On the one hand the necessary AC-DC converter stations cause losses and cost, but on the other hand they provide full power flow control [7].

The state of the art for long distance subsea power transmission is HVDC, and this technology is considered in the remainder of this report if not specified differently.

1.2.2. Technology for Local Offshore Cluster Grids

As part of the North Sea Super Grid, which will span at least a large part of the North Sea, there will also be smaller local offshore grids. These can typically be the internal collection grid of a wind power plant or the internal distribution grid of an oil&gas platform. Also larger offshore cluster grids, which combine several offshore wind power plants and other electrical installations, can be seen as local offshore grids, as long as their geographic extend is small compared to the north sea region and as long as the involved transmission distances do not call for special technical solutions for long distance transmission.

DC Offshore Cluster Grids

DC technology for offshore cluster grids has been considered in literature [8], [9]. This application of DC technology is however not mature yet, and mostly regarded in the academic community. The main driver to implement DC cluster grids is to reduce the total number of conversion stages between wind turbine generator and HVDC cable. Handling complex DC structures like a cluster grid is however more challenging than AC. This option might gain importance in the future, when DC grid technology has reached a more mature level.

Low Frequency AC Offshore Cluster Grids

An offshore cluster grid could also be implemented with LFAC technology. This would however only be meaningful if LFAC transmission is used to connect the cluster to other clusters of to shore. As long distance transmission is mostly regarded to be DC, LFAC cluster grids have not been in focus of the research community.

Regular AC Offshore Cluster Grids

The state of the art for these local offshore grids is regular AC technology. While Medium Voltage AC (MVAC) is considered within wind farms and oil&gas platforms, HVAC is considered for cluster grids. The handling of complex grid structures is easier for AC, experience is larger, risk is smaller, and more components are standardised and available. As long as the aforementioned problems with susceptance of long cables do not constrain the utilisation of proven 50 Hz AC solutions, this technology is preferred.

1.3. Offshore Grid System Design

There are two main possibilities for the topology of the NSSG:

- a true meshed HVDC grid
- a conglomeration of smaller HVDC systems

The first option is the "clean" solution. It could be superior, as being cheaper, having lower losses and requiring fewer HVDC converter stations. However, it would require an advanced protection and control system to ensure reliability. There are ongoing research activities regarding the protection of large meshed HVDC grids, but there is no ready product available on the market. This approach would also require a lot of coordination between all stakeholders involved (e.g. unified voltage level), which seems to be extremely difficult. It would also not enable for the full integration of existing infrastructure.

The second option is a conglomeration of smaller HVDC systems, which are interconnected by so-called supernodes (and possibly also DC-DC converters in the future). This approach relies on proven technology, enable for full control over the system, and avoid the need for DC circuit breakers and advanced DC protection systems. It also requires significantly less coordination, as the subsystems can be planned and constructed individually (e.g. individual voltage levels, control systems, etc.), where only their interfaces need to be coordinated well. This is probably the most realistic option, the most likely to be realised.

A combination of both concepts is also possible, as the HVDC systems within the conglomeration can well be quite large and meshed. This may happen when there is a gradual shift from the second option towards the first option due to technology progress. Since it will take decades to construct a full-scale NSSG, it is likely that different technical solutions will be chosen in the beginning and the end.

1.4. The Outline of this Report

The report contains this introduction and three more chapters. Chapter 2 is treating offshore network components. Chapter 3 is treating offshore network system aspects. Finally Chapter 4 is concluding with a gap analysis and the ways forward.

Appendix A contains collected data on VSC HVDC converters. Appendix B contains collected data on XLPE HVDC cables. Appendix C contains collected data on MI HVDC cables. These data cover the time range until 2020, and is based on projects that are existing, under construction or at least confirmed. These data have been collected from a variety of sources, and accuracy cannot be guaranteed.

Appendix D includes a draft article 'Definition and Classification of Terms for HVDC Networks' submitted to the CIGRE Science&Engineering Journal in May 2015. This article contains a proposal for definitions and classification, which has been elaborated together with partners from the NSON initiative.

2. Offshore Network Components

This section of the report gives a perspective on the available technologies for the realisation of the NSSG. In focus are:

- HVDC cables
- AC-DC converters
- DC-DC converters
- Protection equipment
- Offshore electric energy storage
- Offshore platforms

2.1. HVDC Cables

There are two main types of HVDC cables available in the market:

- Cross-Linked Poly-Ethylene cables (XLPE cables)
- Mass-Impregnated cables (MI cables)

In some projects, also a third special cable type is applied:

- Self-Contained Fluid Filled cables (SCFF cables)

2.1.1. Self-Contained Fluid Filled Cables

Self-contained fluid filled (SCFF) cables have an insulation system consisting of a paper impregnated with a low viscosity fluid (usually oil). This cable type has a central duct where the fluid is maintained under pressure allowing it to reach the insulation. Oil leakage is a potential risk for SCFF cables

These cables can achieve high ratings. Voltage ratings can reach 500 kV and current ratings can reach 2.8 kA as seen at the Kii Channel HVDC Link [10], [11]. This HVDC system was however taken into operation at 250 kV, and an upgrade to 500 kV was announced. SCFF cables are commercially available up to 600 kV by Prysmian [12].

Since fluid is in constant circulation, hydraulic and pumping stations are essential. These oil circulation systems have limitations, and therefore this cable type is not suitable for longs distance transmission. The Kii Channel HVDC link cable is 49 km long [11]. The manufacturer Prysmian offers this cable type up to ca. 60 km length [12]. This implies that the technology is not suitable for building the North Sea Super Grid.

2.1.2. Mass Impregnated Cables

Mass-impregnated (MI) cables use a high-density paper (and in some cases laminated with poly-propylene) impregnated in a high-viscosity fluid as insulation. These cables are in use up to 500 kV in several projects. Current rating has reached 1.66 kA. The Western HVDC Link [13] in the UK under construction will be the first HVDC cable with 600 kV (supplied by Prysmian). However, there are cable manufacturing problems, leading to a delay in the project. Data from MI cable projects until 2020 can be found in Appendix C.

This type of cable does not require circulation of fluid and the length is not limited by the requirements for pumping station as in oil filled cables. For many years, cables with mass impregnated paper as insulation material have been the standard.

2.1.3. Cross-Linked Poly-Ethylene Cables

HVDC XLPE cables have seen very fast developments. Their significance has grown quickly in recent years, and this cable technology if often considered the technology of the future. Polymeric HVDC XLPE cables are manufactured mostly in Europe (ABB and Prysmian) but also in Asia (Furukawa and LS Cables, and also some Chinese manufacturers).

There are several advantages of HVDC XLPE cables compared to mass impregnated cables:

- Smaller bending radius (making the installation and transport easier)
- Possible to have dynamic moving installations (homogenous extruded insulation system)
- Faster manufacturing process (homogeneous extruded insulation system)
- More environmental friendly (no oil leaks)

Voltage Ratings

The development of the XLPE cable DC voltage ratings is visualised in Figure 1. The data until 2020 are taken from confirmed projects. More details can be found in Appendix B.

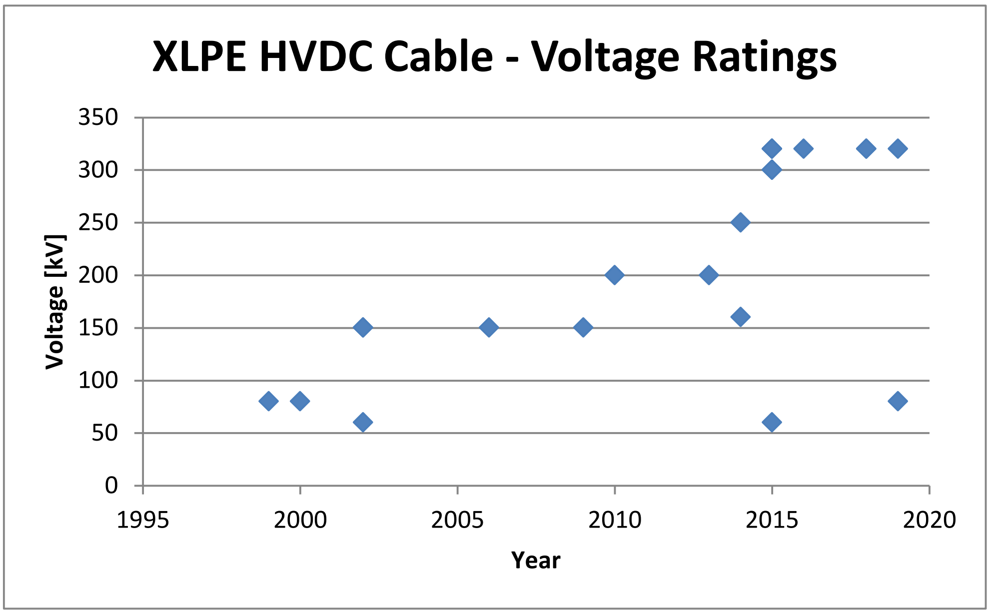

Figure 1: XLPE cable voltage ratings

The voltage level has reached 320 kV, which is in operation (e.g. INELFE [14]) and also under construction in several projects.

Current Ratings

The development of the XLPE cable DC current ratings is visualised in Figure 2. The data until 2020 are taken from confirmed projects. More details can be found in Appendix B.

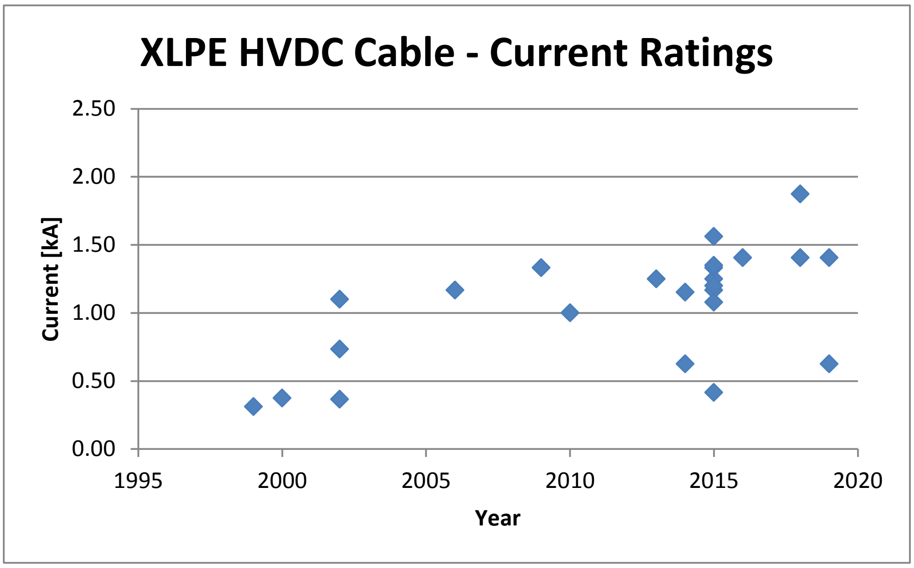

Figure 2: XLPE cable current ratings

The current has not seen such a fast development as the voltage. This was expectable, as increasing the current significantly increases the losses, which counteracts the motivation to do it. The highest current rating in operation is 1,56 kA (INELFE [14]), but in 2018 the Caithness Moray link with a rating of 1,88 kA is expected to become operational.

Power Ratings

The development of the XLPE cable power ratings is visualised in Figure 3. The data until 2020 are taken from confirmed projects. More details can be found in Appendix B.

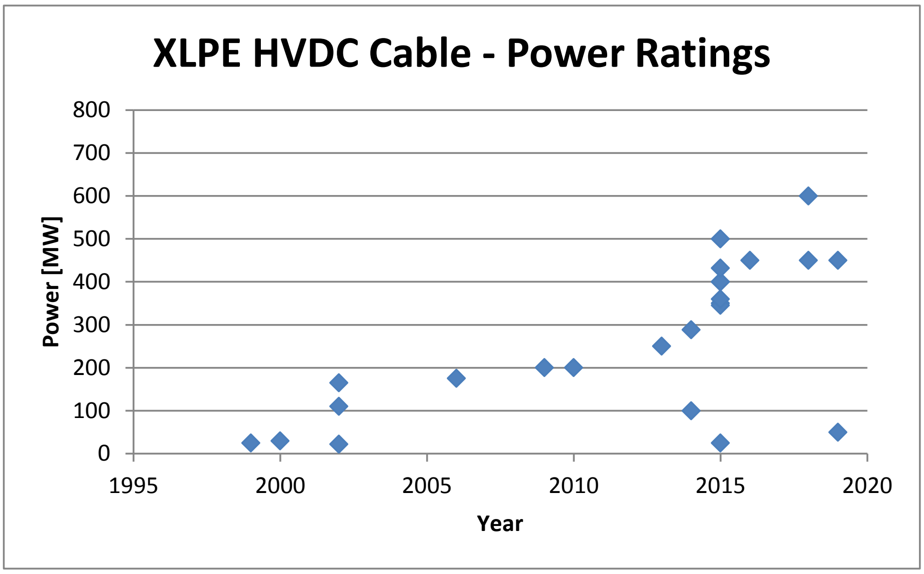

Figure 3: XLPE cable power ratings

Power has reached 500 MW per cable, as applied in the INELFE project. The Caithness Moray project will increase this to 600 MW per cable in 2018.

Ratings Outlook

The combined XLPE cable ratings are visualised in Figure 4. More details can be found in Appendix B.

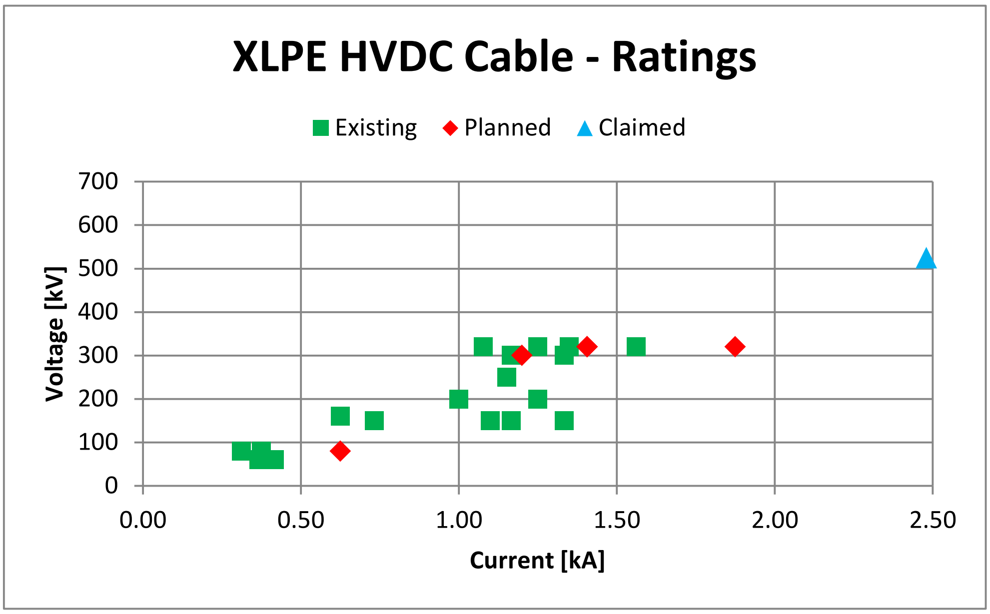

Figure 4: XLPE cable ratings

Even considering all the advantages of XLPE cables, mass impregnated cables have until now always outcompeted HVDC XLPE cables in terms of voltage and current ratings. This will possibly change in the near future; ABB released a new HVDC XLPE cable with a voltage rating of 525 kV and a current rating of 2,5 kA in August 2014 [15]. This newly developed cable boosted possibilities and expectations significantly. If it can prove successful performance in practical applications, it could outcompete mass impregnated cables with expected lower production cost (simpler production process). This cable has the potential to be a game changer for super grids.

The NordLink [16] project will utilise 525 kV cables from ABB, but these will not be the new XLPE cables mentioned in [15]. No reason was officially announced, why the new cable technology was not chosen. Possibly, the manufacturing capabilities for the new cable were not sufficient to keep the project schedule, or the customers require additional long-term testing to gain trust in the reliability of the new cable. At the time of writing, there is no confirmed project which will utilise the new cable.

2.2. AC-DC Converters

The power converters are the interface between AC and DC systems. There are two main technologies for HVDC converters: current source converters (CSC) and voltage source converters (VSC).

2.2.1. Voltage Source Converters

VSCs use semiconductor devices which can be turned on and off independently of the current flowing through them at the time. The switching can be achieved independently of the connected AC voltage so the operation differs considerably from CSC operation (Section 2.2.2). The state of the art is to use IGBTs with anti-parallel diodes, but also other devices like GTOs and IGCTs are possible.

VSCs have several significant advantages over CSCs: They are able to connect to weak and even passive AC grids, and supply black start capability. They have StatCom capability (meaning fast independent control of reactive power) and can significantly support the AC grid's voltage. VSCs do not require large AC filters, which enables for designing compact converter stations. All these mentioned advantages over

CSCs are very important offshore, which makes VSCs the technology of choice for AC-DC converter stations in the North Sea.

VSCs operate at fixed DC voltage polarity, and power flow reversal is achieved by DC current reversal. There is no minimum DC current (as for CSCs), so this reversal (as well as start-up and shut-down sequences) can be conducted in a continuous and smooth way. VSCs are therefore well suited for operation in DC grids, as they can perform the mentioned actions without disturbing the grid's current balance.

The cost and losses of VSCs are somewhat higher compared to CSCs, but these drawbacks are clearly overcompensated by the mentioned advantages, regarding offshore and DC grid applications, but also in other cases.

2.2.1.1. VSC Technology Development

VSC Technology was first demonstrated in 1997, and since then, there have been several generations in the development of this technology as shown in Table 1 [17]. All data in this table is intended as an indication only, and there can be significant differences between different specific projects.

Table 1: Development of VSC HVDC converters

Generation	Manufacturer	Switching frequency	Power losses	Year	Project	Number of Levels
Prototype	ABB	---	---	1997	Haellsjoen [18]	2
First	ABB	39th harmonic	3 %	1999	Gotland [7]	2
Second	ABB	23rd harmonic	1,9 %	2002	Cross sound [19]	3
Third	ABB	23rd harmonic	1,4 %	2006	Estlink [20]	2
Fourth-(A)	Siemens	<3rd harmonic	1,0 %	2010	Trans bay [21]	217
				2015	INELFE [22]	401
Fourth-(B)	ABB	≥3rd harmonic	1,0 %	2014	Mackinac [23]	9
				2015	DolWin 2 [24]	37

First Generation: Two-Level VSCs

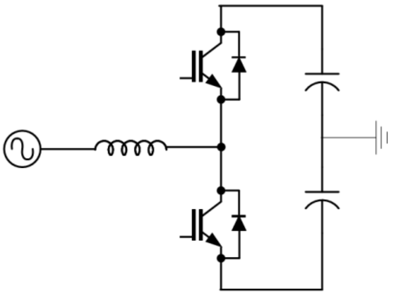

Figure 5: Two-level VSC topology

Two-level VSC is the most simple configuration with the smallest footprint, but it injects high harmonic in the AC voltages, although reduced with higher operating switching frequency at the expenses of higher power losses [25]. The schematic diagram in Figure 5 shows the typical topology of two-level converters.

Second Generation: Three-Level VSCs

Three-level HVDC converters have been built with the neutral point clamped (NPC) topology. The clamping can be done passive with diodes or active with IGBTs. Three-level converters have lower harmonic content and lower power losses than two-level converters. However, they have a larger footprint compared with two-level VSC [25]. Moreover, they have a poor switching utilisation. Figure 6 shows a three-level converter topology.

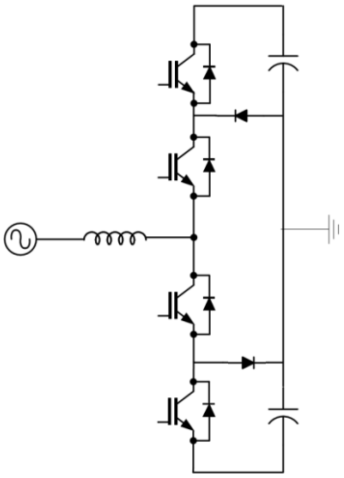

Figure 6: NPC Three-level VSC topology (diode-clamped)

Third Generation: Two-Level VSCs with Optimum PWM

This type of VSC has a similar topology as the regular two-level VSC described before (shown in Figure 5). The difference is the utilisation of the so called "Optimum PWM", which combines elements of programmed selective harmonic-elimination and third harmonic injection. Doing this, losses can be significantly lower as compared to regular PWM switching [17].

Fourth Generation: MMC VSCs

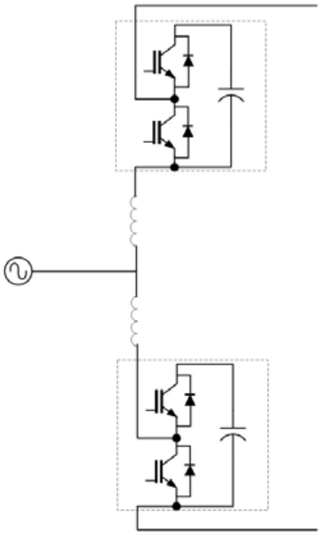

Figure 7: Modular multi-level VSC topology

Modular multi-level converter (MMC) is the most recent multi-level solution for HVDC and to some extent can be considered the state-of-the-art topology for high-power and high-voltage applications. MMC is aimed to reduce the power losses and to reduce the harmonic contents in the voltage and current waveforms. In addition, MMC topology is based on a modular and scalable structure that uses a stack of identical modules. The modular design allows adapting a MMC system to a wide range of DC voltages and enables an intrinsic reliability as it is possible to bypass a module in case of malfunction [26]. Figure 7 shows a typical MMC topology.

The fourth generation can be sub-divided in two types, which (in this report) are referred to as 4a and 4b.

Generation 4a is:

- The 'original' MMC topology
- Introduced by Siemens and now also available from Alstom Grid
- Uses a large number (6* ca. 400) of modules
- Uses small modules (DC voltage ca. 2 kV per module)
- No series connection of IGBTs
- Modules behave like a switched capacitor

Generation 4b is:

- A variation of the MMC called Cascaded Two-Level (CTL) converter
- Offered by ABB
- Uses a small number (6* ca. 40) of modules
- Uses large modules (DC voltage ca. 20 kV per module)
- Series connection of IGBTs inside each module
- Modules behave like a power converter

At the moment, it seems not to be possible to state which of the two topologies is 'better'. Having a smaller number of modules probably makes control easier, as less individual modules need to be controlled. This leads however to larger modules, which are more complex to build and which can be more difficult to transport and replace. Which company offers which topology is probably mostly based on patent rights rather than on advantages or disadvantages of the topologies.

There are several other variations of fourth generation topologies. Today's MMC use half-bridge configuration for each module, but full-bridge modules have also been proposed giving more operational flexibility and robustness at the cost of higher losses and more hardware. There are also concepts of hybrid MMC converters, which combine features of two-level and multi-level converters. These special concepts are however still at an early stage of development.

2.2.1.2. VSC HVDC Converter Project Data

The development since 2010 has not brought a fifth generation, but ratings are increasing significantly.

Voltage Ratings

The development of VSC HVDC DC voltage ratings is visualised in Figure 8. The data until 2020 are taken from confirmed projects. More details can be found in Appendix A.

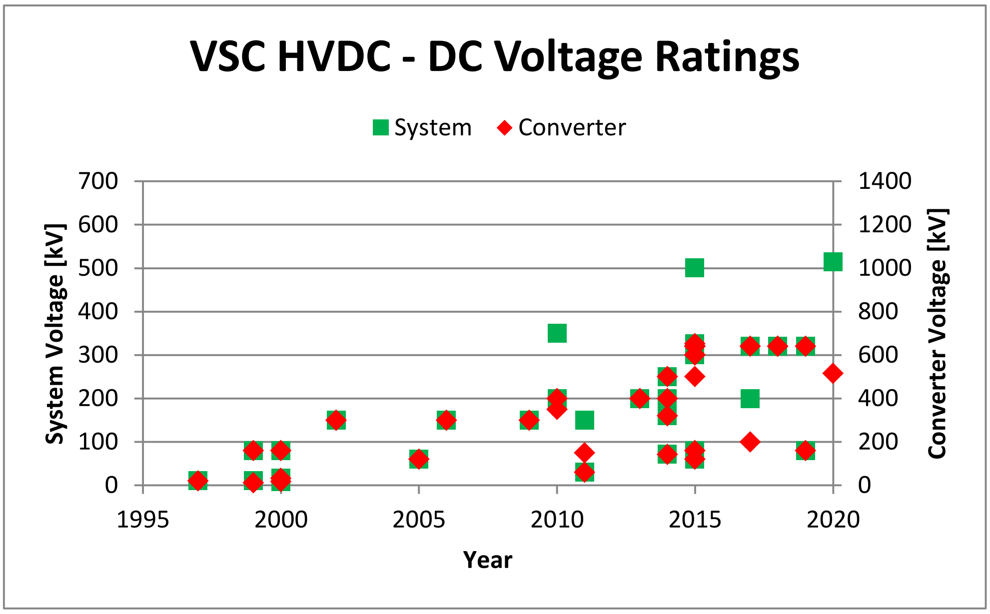

Figure 8: VSC HVDC DC voltage ratings

In Figure 8, both system voltage (line to ground) and converter voltage (positive to negative converter terminal) are displayed. As the majority of VSC HVDC projects use a symmetric monopole configuration, the converter voltage is usually the double of the system voltage.

Converter DC voltage has gone up to 640 kV (±320 kV), and this voltage level is used for many symmetric monopoles under construction. INELFE [14], the first project with this voltage level, has been commissioned and other projects like DolWin1 [27] are in the finalising phase at the time of writing.

System DC voltage has reached 500 kV (voltage to ground) at the Skagerrak4 project [28]. This system could be seen as a regular monopole, but it is operated as half of a hybrid bipole, operating together with the Skagerrak3 CSC system.

The NordLink HVDC system [16] is expected in 2020, and this will increase system voltage to 525 kV. It might possibly boost converter voltage to 1050 kV (±525 kV), but it is likely that the project will be realised with two series connected converters in bipole configuration.

Current Ratings

The development of the VSC HVDC DC current ratings is visualised in Figure 9. The data until 2020 are taken from confirmed projects. More details can be found in Appendix A.

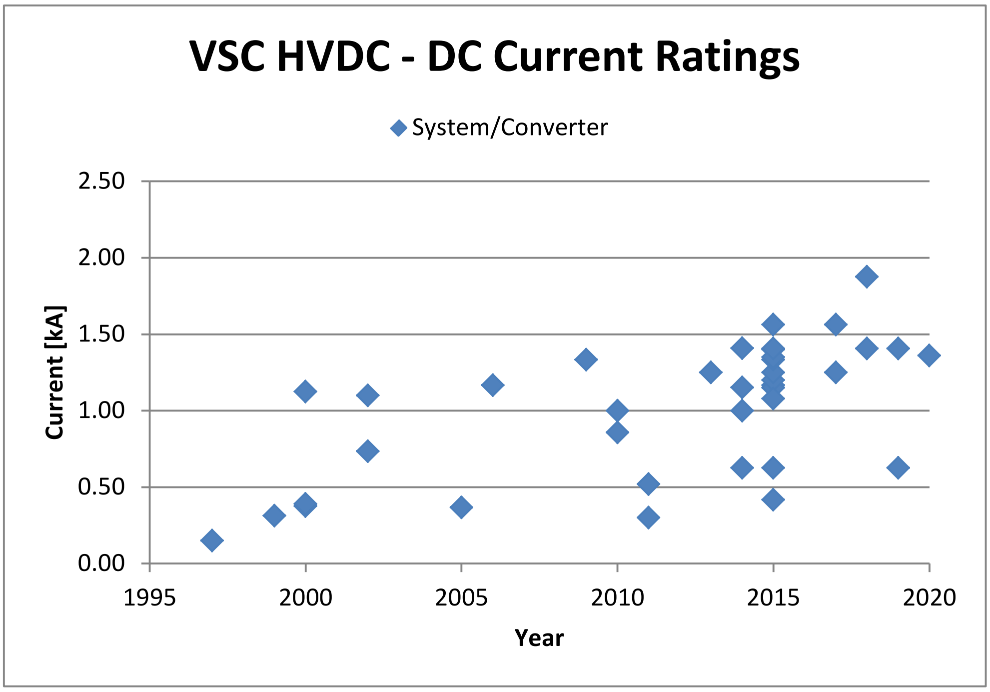

Figure 9: VSC HVDC DC current ratings

In the past years, DC current ratings have not experienced dramatic changes like DC voltage ratings did. This can generally be explained with the small incentive of increasing the current, due to unavoidable conduction losses increasing with the square of the current.

The DC current rating has reached 1,56 kA at the INELFE project [14]. By 2018 the rating is expected to increase to 1,88 kA in the Caithness Moray project.

An interesting case to consider is the Shin-Shinano project from 1999 [29] (project not displayed in Figure 9), which already had a current rating of 3,5 kA, however at a rather low voltage of 10,6 kV. This project was unlike the others not using IGBTs but GTOs as switching elements, which can handle higher currents. It will be interesting to see if thyristor based components like the GTO will find application in modern MMC converters. The generally low switching frequency of MMCs changed the requirements for the switching components of the VSC, possibly in favour of other semiconductors than the IGBT.

Power Ratings

The development of the VSC HVDC DC power ratings is visualised in Figure 10. The data until 2020 are taken from confirmed projects. More details can be found in Appendix A.

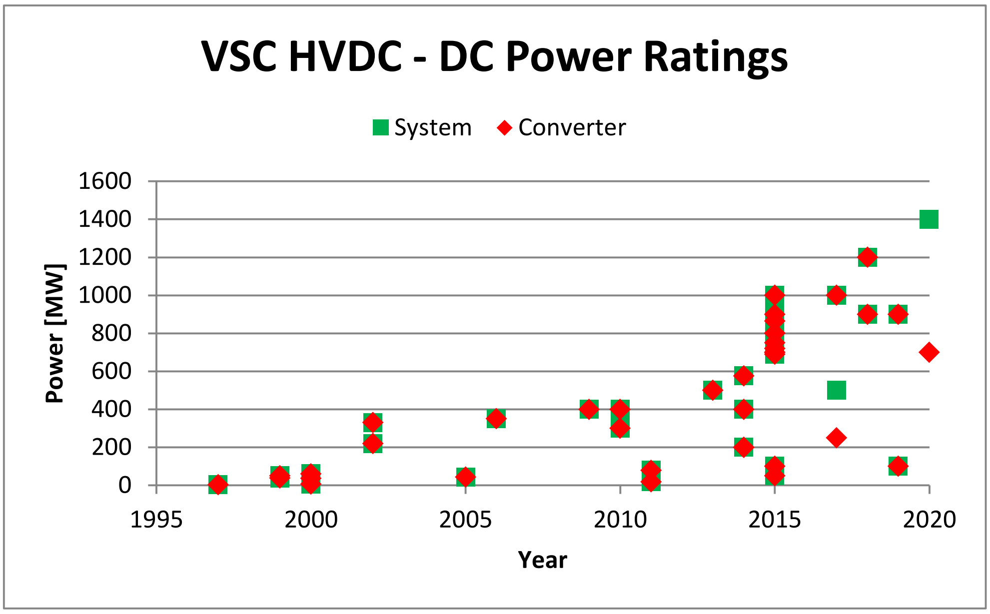

Figure 10: VSC HVDC DC power ratings

Considering the significant voltage rating increases and the moderate current rating increases, it is obvious that power has increased very significant. Converter DC power ratings have gone up to 1000 MW at the INELFE project [14] and are going to reach 1200 MW at the Caithness Moray project [23],[30]. System power is following this development, as the mentioned projects are symmetric monopoles, where converter power and system power are identical.

In 2020, when the NordLink project [16] is expected to be operational, system power will increase to 1400 MW. Converter power might follow this step, if NordLink is realised as a symmetric monopole. It is however likely that a bipole configuration will be chosen.

Ratings Outlook

The combined VSC HVDC ratings are visualised in Figure 11. More details can be found in Appendix A.

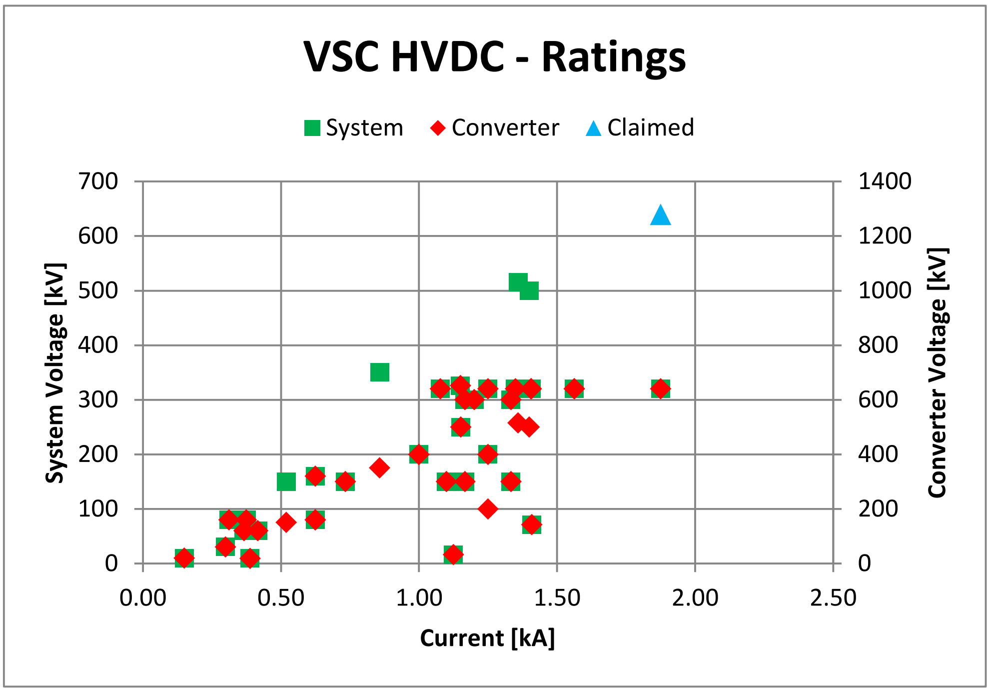

Figure 11: VSC converter ratings

The two projects with the noticeably highest system voltage (the two green diamonds on the top of the figure) are Skagerrak4 (500 kV) [28] and NordLink (525 kV) [16]. The project with the highest current (1,88 kA) is the Caithness Moray link (double marker on the right of the figure). Combining these maximum current and voltage ratings implies, that a 2000 MW bipole link should be possible.

ABB claims that also 2400 MW at ±640 kV is possible [31], but this is not considered in current projects yet. This is probably due to the fact that no cables are available for 640 kV, and that the market for overhead-line based VSC HVDC has been very limited until now.

It seems that from now on, the limiting factor for DC voltage will be the cables rather than the converters. The voltage ratings are very unlikely to continue to increase at the same pace as they did before. This could possibly trigger a development towards higher currents. Here thyristor based switching components such as GTO or IGCT could possibly come into play.

2.2.2. Current Source Converters

CSC-based HVDC is a well-established mature technology which was introduced for the first time in 1954. It is very suitable for long distance transmission of bulk power, due to its capability of handling high voltages and high currents with low losses. Its reliability and availability has been demonstrated for many years. Among the CSCs, the line-commutated converter (LCC) is the most established and widespread technology around the world.

CSC uses thyristors as valves. These solid-state semiconductor devices are able to conduct current if the anode voltage higher than the cathode voltage (similar to a diode). The conduction process cannot be started without an initial signal applied to the gate terminal. It is important to remark that the gate is only able to control the thyristor turn-on, not the turn-off. Once the conduction process has started, the valve will continue to conduct until the current through it drops to zero and the reverse voltage bias appears across the thyristor.

The layout of a LCC-based HVDC transmission system is shown in Figure 12. The key components are converter station (valve hall), transformers, harmonic filters and shunt capacitors. The footprint of such a station is rather large (e.g. 200 m * 300 m).

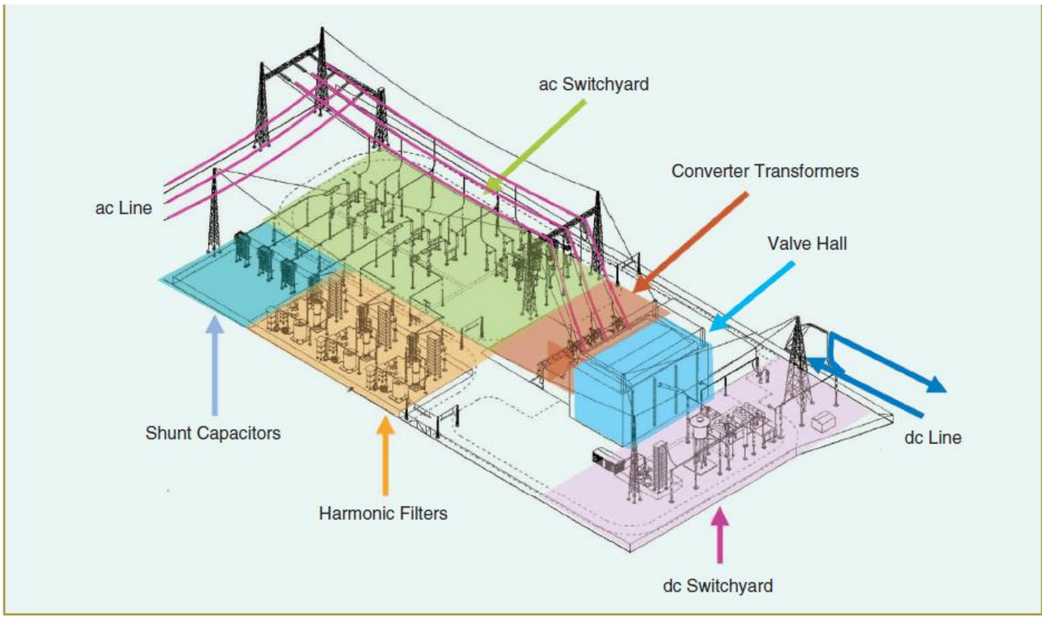

Figure 12: LCC-based HVDC transmission [32]

CSCs Offshore

CSCs require large passive AC filters for proper operation to mitigate produced harmonics and to supply the needed reactive power. This increases the footprint of the installations and implies enormous platforms for offshore applications.

CSCs need an external commutating source voltage for the proper operation, so they can only connect to AC grids with significant short circuit capacity. This means that the CSC is unable to supply passive loads and it does not have black-start capability. It also implies that connection to weak local offshore AC grids is problematic.

The application of CSC technology on offshore stations is mostly disregarded by the scientific community, due to the combination of these two mentioned disadvantages.

CSCs in Hybrid HVDC Links

In recent literature, the feasibility of grid integration of offshore wind farms using hybrid HVDC systems composed by voltage source converters (VSC) and line-commutated converters (LCC), have been investigated [33], [34], [35] (shown in Figure 13). Such a hybrid HVDC systems are attractive mainly because of their lower power losses compared to VSC-based HVDC systems.

However, hybrid HVDC systems have serious limitations when an AC fault occurs at the LCC [34]. This type of fault can produce a commutation failure at the LCC which incurred in a short circuit of the DC side. It is a well-known fact that, in this case, the DC current of the LCC climbs up quickly while the free-wheeling diodes of the VSC provides a path to feed the current into the fault, and hence, no control action can be performed to alleviate the disturbance [34].

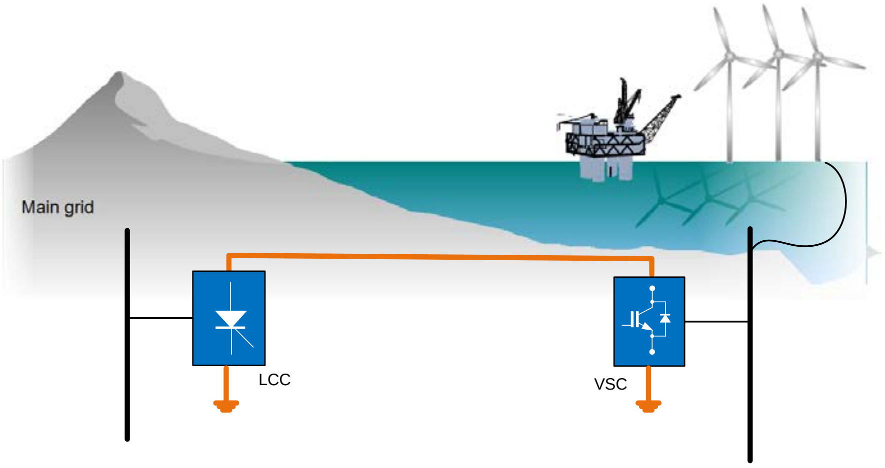

Figure 13: Hybrid HVDC concept

The hybrid concept could also be applied for multi-terminal DC systems. One onshore LCC converter could feed the grid with power, which has been collected from two or more offshore wind power plants, which are connected to the multi-terminal DC system with VSCs.

Another interesting constellation for a multi-terminal hybrid HVDC system is a wind power plant, that connects with a VSC onto an existing LCC-based HVDC link. For this application the full bridge MMC is advantageous, as it can easily cope with the changing voltage polarity of a LCC-based HVDC link. The moment of polarity change still would pose a challenge, as there is no sink for the power produced by the wind farm at that time.

CSCs in DC Grids

A CSC operates with a fixed current direction. For point-to-point connections, power flow reversal is achieved by changing the voltage polarity. For a HVDC grid with fixed voltage polarity, this is not possible, so a power flow reversal cannot be achieved without shut down, reconfiguration (inversion of +/- terminals) and restart of the converter. This indicates that the integration of CSCs into a DC grid can be challenging if power transmission in both directions is desired.

CSCs cannot operate at zero DC current. Taking a CSC into or out of operation is somehow creating a DC current step. For a CSC-based point-to-point HVDC link, this is taken care of with specific procedures for power up and shut down of the system. For a CSC in a DC grid (that needs to operate without interruption), this DC current step creates a disturbance to the grid's current balance. This operation would therefore need to be coordinated with the other converters of the grid (or at least one of them). This is violating the idea of plug-and-play operation of a grid with independent components.

The application of CSC technology for DC grids is mostly disregarded by the scientific community, due to the combination of these two mentioned disadvantages.

2.2.3. Alternative AC-DC Conversion

Another option to achieve HVDC transmission voltage is the dispersed converter concept with series configuration of medium voltage DC devices (shown in Figure 14). Such a series connection leads to the lowest losses [8]. However, the total losses are not competitive with DC parallel connections due to the losses in the converters.

As a consequence of that, the efficiency of the converter must be improved in order to make series connection a practical alternative. One proposal is to use a reduced matrix converter (RMC) which transforms the three-phase voltages and currents in a square wave, high frequency single phase output [36].

A high frequency transformer is used for galvanic isolation and to raise the output voltage. A full-bridge diode rectifier is used as an AC-DC converter to connect the conversion system with the output DC grid.

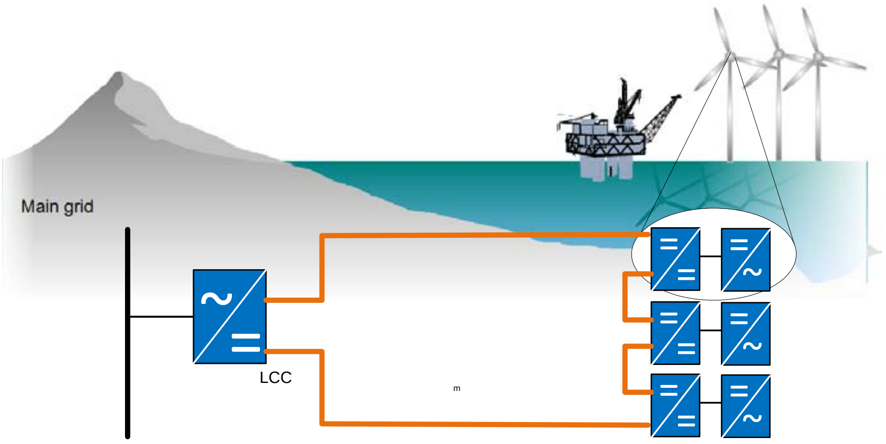

Figure 14: Series configuration concept

2.3. DC-DC Converters

There are several different voltage levels in today's AC grids, and transformers are used to connect those voltage levels. A future DC grid with more than one voltage level will also create the need for connection between those levels. However, voltage transformation is far more complicated for DC than for AC. This is actually one of the major reasons why AC won the "battle of the currents" more than a century ago.

Even though standardisation efforts are made, to unify voltage levels and to avoid the need for DC-DC conversion, different voltage levels will still appear. Already today several different DC voltage levels are applied for offshore wind integration in Germany. These point-to-point links would need some kind of conversion to be integrated into a future North Sea Super Grid. The fast progress in converter and cable technology also implies that significantly higher voltages will be achievable in the future. Only utilising a defined "standard voltage" would waste possible benefits from improved future voltage ratings.

There are generally two possibilities to connect two different DC voltage levels:

- With a DC-DC converter
- Through regular 50 Hz AC with an DC-AC converter and an AC-DC converter

A DC-DC converter is likely to be cheaper and more efficient than two separate converters with regular 50Hz AC in between. The second solution however also creates a regular 50 Hz AC bus in addition to interconnecting the two DC busses. This 50 Hz AC bus can be connected to any other AC facilities at the location like an offshore wind power plant or the onshore continental grid. The DC-DC converter solution will therefore be mostly relevant AC integration plays a minor role. This could typically be where no AC grid exists or where the AC grid is small and weak. This is likely to be offshore.

A DC-DC converter can not only connect two different voltage levels but also regulate the current or power flow through the converter, which helps to operate a meshed DC grid. It could even be applied for this purpose only, connecting two busses of the same voltage level. For this task however, also other specialised device topologies are possible, called DC current flow controller [37].

DC-DC converters topologies can be effectively classified into two groups:

- Isolated DC-DC converters
- Non-isolated DC-DC converters.

2.3.1. Isolated DC-DC Converters

An isolated DC-DC converter uses galvanic insulation between the input and the output port. It typically consists of two AC-DC converters connected to each other by a transformer. Examples of possible topologies are shown in Figure 15. The switching frequency and the frequency on the AC side are main design parameters. AC frequency is typically higher than the regular 50Hz. Indeed a high frequency allows for a significant reduction of the size and volume of the transformers and of the energy storage components (capacitors and inductors). However, a higher frequency leads to higher power losses and to a more complex design and manufacturing of the transformer (e.g. amorphous core materials, Litz wires) [38], [39].

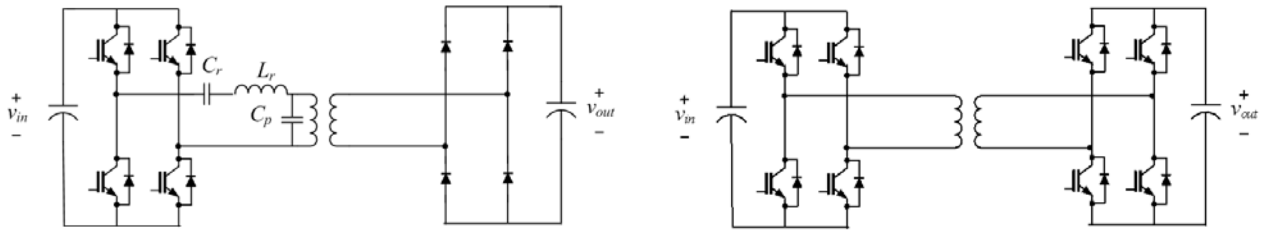

Figure 15: Isolated DC-DC converters
left) Resonant bridge converter – right) Dual active bridge converter

Availability on the market of DC-DC converters for high power applications as standard products is rather limited. In literature several prototypes have been presented spanning from tens of kVs to a few MWs and with an AC operating frequency in the kHz range using several topologies [40], [41], [42], [43], [44], [45]. The most mentioned topologies for isolated DC-DC converters in literature are: single active bridge, dual active bridge and resonant bridge [38], [8]. Recently, topologies using MMCs have been proposed [46].

2.3.2. Non-Isolated DC-DC Converters

Non-isolated DC-DC converters are structurally simpler than isolated converters which lead to lower costs and sizes [39]. Two topologies are shown as an example in Figure 16. However, these converters are not suitable when there is a large difference in the voltage between the two DC grids since they can only achieve a limited voltage ratio. The limitations in the voltage gain and the lack of galvanic insulation reduce the relevance of these topologies for DC grid applications.

Classical buck and boost DC-DC topologies are not suitable for high power since they require large duty cycles at higher conversion ratio which lead to low efficiency and reliability. There are some proposals in the literature, for example a switched capacitor multilevel DC-DC converter has been proposed in[47]. The main limitations are mentioned in [39], among them the lack of bidirectional power and modularity are the main drawbacks.

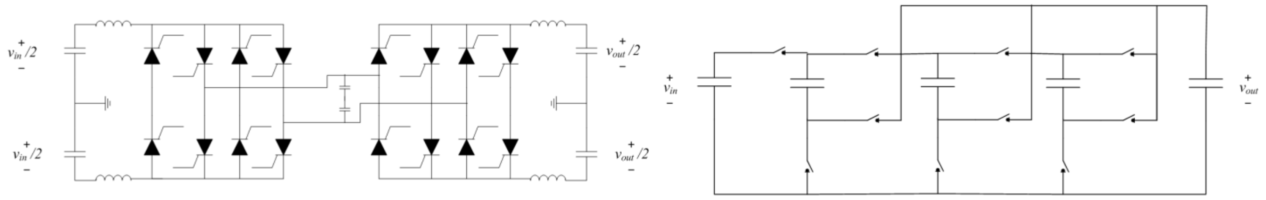

Figure 16: Non-isolated DC-DC converters
left) Bidirectional high-power DC transformer [48]
right) Modular multi-level capacitor-clamped DC-DC converter [49]

A modular multilevel capacitor clamped converter was proposed in [49]. The advantages of this topology are: modular design, bidirectional and high frequency operation and low current ripple at input and output. However, the main drawback according to [39] is the unequal voltage stress at the switches. There is also soft-switched transformer-less topologies using thyristors. The main disadvantage is the large resonant capacitor needed which is reflected in the cost and footprint. In [39] more topologies using thyristors are shown but only for step-down operation mode. Recently, topologies using MMCs have been proposed [46] which is best suited to low ratio applications.

2.4. HVDC Protection Equipment

Any grid needs a reliable protection system. The main equipment which is needed to build such a protection system is treated in this section. The development of protection equipment for DC systems is more challenging than for AC systems, mainly due to the absence of reactance and current zero-crossings. There has also been little reason to develop such equipment in the last century due to a lack of DC grids. This can explain why protection equipment for DC systems is still immature. The three types of protection devices treated here are:

- Circuit breakers
- Fault current limiters
- Grounding electrodes

2.4.1. Circuit Breakers

In the past decades the development efforts in DC circuit breakers (DCCB) technologies for high-voltage applications have been relatively limited mainly due to the lack of a market demand. However, this has now changed because of the market needs for multi terminal HVDC systems based on VSC.

The development of DC breakers has been a great challenge due to the demanding requirements:

- Fast response
- Actively forcing the current down to zero
- Dissipation of a large amount of energy
- Withstanding the transient voltage response of the system after the interruption

The current available options for DC circuit breakers are:

- Resonance-based circuit breakers
- Solid-state circuit breakers
- Hybrid DC breaker.

Mechanical circuit breakers, as they are applied for AC systems, do not work for DC system, as they need a current zero-crossing to function.

Resonance-based Circuit Breakers

Resonance-based DC circuit breakers use conventional AC breakers connected in parallel with a commutation path (LC series) and an energy absorption path (varistor). Resonant breakers are still limited in interruption current and interruption time [50]. They are not suitable for multi-terminal HVDC applications since they cannot ensure a sufficient reaction time [51]. However, this technology has been successfully tested for point-to point HVDC installations [52].

Solid-state Circuit Breakers

Solid-state circuit breakers use a stack of semiconductor switches (e.g. IGBTs) connected in parallel with a string of varistors. The breakers are closed (IGBTs turned on) during normal operation and the current flows through the semiconductor devices. During breaking operations, the semiconductor devices are turned off. The voltage rises abruptly but the string of varistors protects the devices from over-voltages and dissipates the inductive energy.

A solid-state circuit breaker can be seen as being very similar to an arm of a two-level HVDC converter. A main drawback of a solid state breaker is the conduction losses due to the high number of switches to be connected in series to sustain HVDC voltages.

Hybrid Circuit Breakers

At the end of 2012, the development of a new high voltage DC breaker was announced by ABB [53], [54]. The so-called hybrid DC circuit breaker (shown in Figure 17) aims to combine the fast operation of a solid state breaker with the low conduction losses of a mechanical circuit breaker into a single device.

The hybrid circuit breaker includes a string of IGBTs rated to break the fault currents and sustain over-voltages. The components count should be doubled if the device needs to sustain voltage of both polarities as in any solid state-based DC breaker. A string of varistors is connected in parallel to protect the devices from transient over-voltages and dissipate the inductive energy of the grid during breaking operations.

However, these two paths are active only during breaking operations. An additional path composed by a very fast mechanical switch and another solid state device (load commutation switch) acts as a bypass and conducts the current during normal operations. The load commutation switch is rated for sustaining a voltage equal to the on state voltage of the main IGBT string (in the kV range) and requires a much lower number of semiconductor devices in series compared to the main breaker (e.g. 1/300). Thus, the forward voltage drop in the conduction path and the related conduction losses are strongly reduced. The Figure 17 shows a schematic of the hybrid DC breaker.

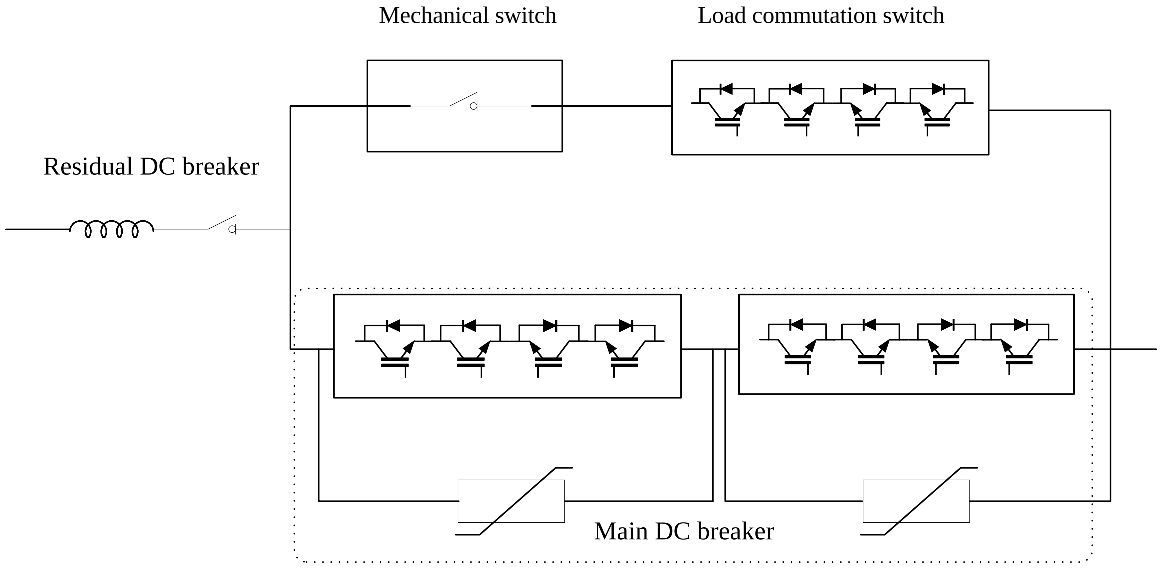

Figure 17: Hybrid HVDC breaker

2.4.2. Fault Current Limiters

Fault current limiters (FCL) are devices which limit the fault current to levels that can be interrupted by the protection devices. These devices are generally applied in AC systems, but some concepts could also be used for DC. For AC systems, there are two general types of FCLs, and these two are based on:

- Resistance
- Reactance

The reactance based concepts cannot directly be translated to DC systems, since the phenomenon of reactance does not exist for DC. The resistance phenomenon is similar for DC and AC, which indicates that resistance based concepts could also be applied for DC systems.

Generally, non-linear properties are desired for FCLs, as the goal is to have no influence on regular operation and sufficient influence on fault-operation. But also linear components can be used for limiting the fault current.

Inductors

Inductors are a simple and cost effective solution to limit the fault current in any power system device. Inductors are normally used in substations or feeders in the ac power grids. However, this linear solution increases the power losses, as it permanently carries the full current [55].

Considering DC, an inductor does not provide reactance, which can limit the fault current in steady state, as in does in AC. It can however reduce the peak of the transient current resulting from the discharge or the system capacitance. This is however only partly relevant, as the protection system needs to take countermeasures before that peak is reached. It also reduces the rate of change of current, meaning that the fault limit will rise more slowly. This is an important feature, as it gives the protection system more time to react, before the fault current reaches critical levels.

Polymeric Positive Temperature Coefficient Resistor-based FCL

Polymeric Positive Temperature Coefficient (PTC) resistor-based FCLs are non-linear resistance based devices. The polymer composite contains conductive particles dispersed therein which are in contact with each other under ambient temperature. These conductive particles provide a path for the current. So, the polymer composite has a low resistance under normal conditions.

When a fault occurs, there is a significant increase in the current and thus also temperature increases. The polymer composite expands with the increase in the temperature and the conductive particles are disconnected causing a high resistive path [56]. It remains to be investigated if this technology can be up-scaled for high voltage high current applications.

Liquid Metal FCL

Another concept is the liquid metal FCL which is a non-linear resistance based device. It uses the principle that the liquid metal changes its states from liquid to vapour when the current increases significantly [56]. Under normal conditions, the liquid metal has low resistance. When a fault occurs, part of the liquid metal becomes vapour due the increase of the temperature. The change of state provokes high resistance path. When the fault is cleared, the high current is interrupted and the vapour becomes liquid again.

Superconductive FCL

Superconductive FCLs are highly non-linear resistance based devices. The material exhibits a superconductive state, near zero resistance at normal conditions and normal state, high resistance, when a fault occurs. Under normal conditions, the resistance is near to zero but the superconductive material requires a cooling system to regulate the temperature. When a fault occurs, the fault current heats the superconductive material and reverts to its normal state, i.e. high resistance. The high resistance is able to limit the fault current to levels which are suitable for the protection system [56].

Fault Current Limiting HVDC converter control

The concept mentioned here is not a FCL device, but it is a control concept for HVDC converter stations, that can have a similar functionality as FCLs. This concept is described in [57], and it proposes a specific fault control for the converter, which is completely different form normal operation control.

The mentioned FCL devices, which are all series devices, reduce the fault current through the line which they are connected to. The fault limiting control applies to a HVDC converter, which appears as a shunt device in the DC system. It can therefore not limit the fault current on a specific line, but it can reduce the fault current contribution from a specific converter.

The main idea is to utilise the existing L and C components in a HVDC converter station to create a tuned LC circuit (tuned for 50Hz), that blocks the AC side from feeding current into the DC fault. However, this resonant circuit could create high circulating currents within the converter, what could pose a threat to the semiconductors. It is also to be investigated how much the 50Hz tuning of the L and C components is conflicting with the specifications for normal operation of the converter.

2.5. Offshore Electrical Infrastructure Installations

Offshore HVDC converters or transformers and associated equipment require an offshore platform to house them. There are a few examples of HVDC equipment on an offshore platform, for instance Troll-A, which is an oil&gas platform, and BorWin Alpha, the first wind power plant HVDC connection of the world.

A potential future alternative to building an offshore platform would be to place the installations on the sea floor. This could reduce the cost as the platform with foundation is omitted, but it would pose serious restrictions for maintenance and repair. This technology is still at an early stage.

Even though offshore platforms are not really offshore networks components (in the sense that they are not electrical installations), an introduction is given here, as the platforms account for a significant share of the cost of an offshore network.

2.5.1. Foundations for Offshore Platforms

Foundation technology is chosen based on site conditions and platform properties. The main relevant site conditions are water depth, wave heights and currents. The main relevant platform properties are size and weight. There are six basic types of offshore foundations:

- Monopiles
- Tripods
- Tripiles
- Jackets
- Gravity foundations
- Floating foundations

The first three are used for wind turbines, but not for larger installations such as offshore HVDC converter stations or transformer stations. The other three are also used for wind turbines, but can also be up-scaled for transformer and converter station applications. A short description of these three types is presented here.

2.5.1.1. Jacket Foundations

Jacket foundations consist of a truss frame made of many tubular members that are welded together. Piling is driven through each leg of the jacket into the seabed (or through skirt piles at the bottom of the foundation) to secure the structure against lateral forces.

Jacket foundations have been applied to wind turbines (as an example) in the Alpha Ventus offshore wind power plant, as shown in Figure 18. Each jacket carrying one of the 5 MW wind turbines weighs about 320 tons.

Figure 18: Jacket foundations at Alpha Ventus [58]

Jackets have also been successfully applied for larger objects than wind turbines. For instance, the 400 MW HVDC station BorWin alpha (shown in Figure 19) weighs around 3.200 tons, and the jacket another 1.700 tons.

Figure 19: Jacket foundation for BorWin Alpha [59]

The oil&gas industry has applied jackets for even heavier platforms, like the North Rankin B platform, which weighs about 25.000 tons without the jacket (shown in Figure 20).

Figure 20: The North Rankin B platform with jacket [60]

2.5.1.2. Gravity Foundations

Gravity foundations are structures that use their weight to resist wind and wave loading. They are usually made of reinforced concrete and, they are often filled with gravel and stones to increase weight and stability. The main advantage of Gravity foundations is that they are not so expensive to build, due to the low price for concrete. However, the installation costs are higher, due to their weight, and the need for subsurface preparation.

Gravity foundations have been used for offshore wind turbines (shown in Figure 21), like at the Thornton Bank wind power plant.

Figure 21: Gravity foundations for wind turbines [61]

An example of a gravity foundation at a non-wind-turbine application is the well-known Lillgrund transformer station (shown in Figure 22).

Figure 22: Lillgrund transformer station [62]

For even bigger platforms (DolWin beta: 75 m * 100 m, 10.000 tons without foundation), the corresponding gravity foundations (another 13.000 tons) become difficult to lift. An innovative solution to this lifting problem is applied by Aibel, by designing DolWin beta as a self-installing platform (shown in Figure 23).

Figure 23: DolWin beta in Haugesund, Norway [63]

The technical limitations for gravity foundations can be pushed quite far, with the Troll A platform [64] (in total 1.200.000 tons) being the most extreme example (shown in Figure 24). However, the cost of installations like Troll A are far beyond what can be justified for offshore electrical grid infrastructure.

Figure 24: Gravity foundation of Troll A under construction [65]

2.5.1.3. Floating Foundations

Since the cost of all bottom-fixed foundations increases more than linear with water depth, it is intuitively understood that at some depth, it will be a better choice to utilise a floating foundation rather than a bottom-fixed one. At what depth this break-even-point is located is unclear yet, mostly due to limited experience with floating foundations. A floating foundation has some degrees of freedom for movement, but it is held in place by an anchoring system. There are several alternative designs with examples shown in Figure 25.

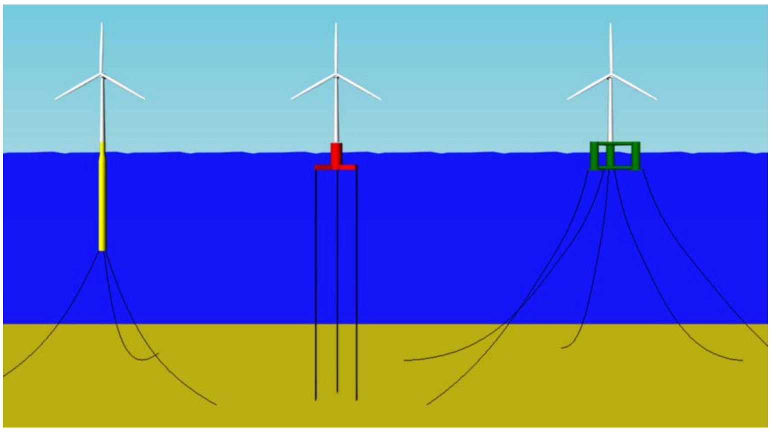

Figure 25: Floating foundations for wind turbines [66]

In the southern parts of the North Sea, the waters are shallow (< 50 m). Offshore wind power plants are preferably planned in shallow waters, as water depth significantly influences foundation costs. The majority of offshore wind activities in the North Sea is therefore concentrated in the southern part. In these shallow waters, bottom-fixed foundations are more suitable than floating foundations.

In the northern part of the North Sea, water depths are around 100 m. There is little wind power activities there today, but if development would pick up in the future, floating foundations will have to be considered and compared to bottom fixed solutions.

In the Norwegian trench along the Norwegian coast, water depths go down to 700 m (in the Skagerrak). There are no concrete plans for large scale offshore wind power plants in these deep water North Sea regions, but possible future activities will surely be based on floating concepts.

When considering floating foundations for electrical installations, one important restriction has to be regarded: Floating electrical installations usually cannot be connected to MI-type power cables (Section 2.1.2), as those are not flexible enough to cope with the movements of floating structures.

For offshore wind, floating concepts are in an early stage of development. A pilot turbine called Hywind was placed in waters off Norway in 2009 (shown in Figure 26). The foundation consists of an 8.3 m diameter, 100 m long submerged cylinder secured to the seabed by three mooring cables. Another pilot project in the wind industry is Blue H which consists of a two blade turbine placed on top of a buoyant, semi-submerged steel structure attached to a counterweight on the seabed.

Figure 26: The Hywind wind turbine floating foundation during transport [67]

There is an offshore wind power plant demonstration project in Fukushima, which is installing floating wind turbines and even a floating transformer station (shown in Figure 27). Similar floating foundations could in theory be also applied for converter stations.

Figure 27: Floating transformer station in Japan [68]

Floating platform technology has also been successfully applied in the oil&gas industry, like the Perdido platform (9.500 tons) place on a floating spar (another 22.000 tons) in the Gulf of Mexico (shown in Figure 28).

Figure 28: The Perdido Spar during Transport [69]

2.5.2. Installation of Offshore Platforms

Offshore operations are very costly compared to onshore operations. They are also heavily restricted by weather and wave conditions. This directly leads to the strong desire to do everything onshore that can be done onshore. This is usually done at a specialised harbour.

Components are either transported to the construction site or manufactured on sight to avoid the need for transportation. On the construction side the offshore platform is assembled. When this work is finished, the platform is transported offshore and installed. The complexity and the cost of this operation are highly dependent on the platform weight.

There are basically three strategies for installing a platform offshore:

- Lifting the platform onto the foundation by a crane vessel
- Floating the platform over the foundation and lowering it onto it
- Utilising a Self-installing platform

Crane Vessels for Offshore Installations

The world record for the heaviest lift was set in 2004, when the vessel 'Saipem 7000' lifted the Sabratha oil&gas platform (12.150 tons) and placed it on its foundation. There are however only two vessels in the world capable of such an operation (the other is called 'Thialf'). Involving those is very costly and can cause delays due to limited availability of the vessels. The vessel availability has generally become a critical bottleneck due to increasing offshore activities, where offshore wind is competing with oil&gas on the same resources. More information on various types of vessels for offshore operations (also other than crane vessels) can be found in [70].

Float-over Installation

An alternative installation method to avoid the utilisation of heavy lifting crane vessels is the so-called float-over method. The platform is placed on floating barges at the harbour and then transported offshore. There it is floated over its foundation and lowered onto it. The designs of the barges and the foundation have to be well coordinated, to make this manoeuvre possible. This method can also be applied to platforms which are too heavy to lift.

Self-installing Platforms

Another option is a self-installing platform like DolWin beta. Here the platform and foundation are assembled at the harbour. The entire construction is designed in a way, that it can float to its destination, where mass is added to make it sink onto the sea floor.

2.5.3. Subsea Installations

It has been proposed to place the electrical installation on the sea floor instead of above the surface. This has several advantages:

- No expensive foundation needed
- Not exposed to storms and waves
- Very little environmental cycles (almost constant temperature)

However there are also significant challenges involved:

- All equipment has to be capsuled
- All equipment has to withstand hydrostatic pressure
- Maintenance and repair is extremely challenging

This subsea approach has been a hot topic in the oil&gas industry, and significant R&D efforts are being made there. This benefits the offshore wind industry, which might at a later stage reuse this knowledge. However, (to the knowledge of the authors) no offshore wind project is considering subsea transformer or converter stations to date. This is most likely due to the immature stage of the technology and the fact that wind power plants usually are built in shallow waters, where the advantages of the subsea approach are smaller.

2.6. Offshore Electric Energy Storage

Intermittent sustainable energy sources pose a challenge for matching production and consumption of electrical power at all times. Specific regions can utilise import and export of electricity to realise regional balancing, however global production and consumption still have to match. The utilisation of import and export for regional balancing is demanding for sufficient power transfer capacities, leading to additional transmission infrastructure cost. With better internal balancing within the region (North Sea in this case), the transmission infrastructure cost can be reduced.

There are generally three principles that can be used for balancing:

- Regulation of non-intermittent sources (thermal power stations)
- Regulation of load (demand side management)
- Energy storage

All three principles are very important for the electricity supply of the future to insure that power is available as needed. However, when focussing on the North Sea, conventional power stations are not foreseen offshore in large scale. Regarding dispatchable loads, it is very unlikely that the connected loads from the oil and gas sector can be dispatched. This leaves the focus for this report on offshore energy storage.

There are many storage options available such as pump hydroelectricity storage, batteries, superconductors, flywheels, regenerative fuel cells, and compressed air energy storage. However, large-scale energy storage needs technologies capable of providing bulk power for long duration at low cost. The most inexpensive storage media such as air or water are seen as economically favourable, bringing the focus towards compressed air energy storage and hydroelectric storage.

Although some emerging battery technologies may provide energy balancing services as well, typical system capacities and storage sizes are an order of magnitude smaller than above mentioned storage systems with significantly higher capital costs [71].

Table 2 shows a comparison of the most suitable options for offshore energy storage systems.

Table 2 Costs for Energy Storage Options (from 2008) [71]

Technology	Capital Cost: Capacity ($/kW)	Hours of Storage
Compressed Air Energy Storage (300 MW)	580	40
Pumped hydroelectricity (1000MW)	600	10
Sodium Sulphur Battery (10MW)	1720-1860	6-9
Vanadium Redox Battery (10MW)	2410-2550	5-8

The main remaining question is "why to place storage facilities offshore and not elsewhere?", as offshore installations generally are more expensive for construction, operation and maintenance. The most important possible reasons are:

- To reduce power flow fluctuations between offshore clusters and onshore grid
  - Making offshore clusters appear as reliable dispatchable power sources
- To implement so-called "peak-shaving",
  - reducing the need for offshore transmission infrastructure
  - avoiding to spill energy, unlike peak shaving with wind curtailment
  - increasing the capacity factor of transmission infrastructure (even more than curtailment)
  - reducing line loading peaks also onshore in coastal regions
- To use the potential of special geologic formations if they are located offshore
- To avoid public opposition against new infrastructure projects
- To reduce onshore land use at densely populated areas
- To utilise deep water hydrostatic pressure as main force for energy storage

The focus in this section is on hydrostatic pressure based storage technologies, as only these technologies are specific "offshore" technologies, while the others are onshore technology taken offshore.

2.6.1. Compressed Air Energy Storage

A compressed air energy storage (CAES) plant consists of a power train motor that drives a compressor to compress air into a reservoir, a high pressure turbine, a low pressure turbine-generator set and heat exchangers as shown in Figure 29. When the air is compressed, its temperature will increase. In a conventional CAES plant, this heat is lost to the surroundings when the hot air is transported to the storage cavity. This leads to lower cycle efficiency since the heat energy is lost. To increase the power output of the plant, the compressed air is fed into a gas turbine cycle, which consequently replaces the lost heat energy. Such a system is a hybrid solution in between a CAES and a gas turbine.

A more modern solution is by storing the heat generated in a thermal storage unit. In this way, heat can be returned to the air before its expansion in the turbine. This method is called adiabatic storage and is aimed to increase the efficiency.

One general advantage of CAES is the minimal visual impact since these facilities are usually located underground in a solution mined cavern, a porous rock stratigraphic or a structural trap. The utilisation of exhausted natural gas reservoirs is being discussed, a concept also promising in the North Sea.

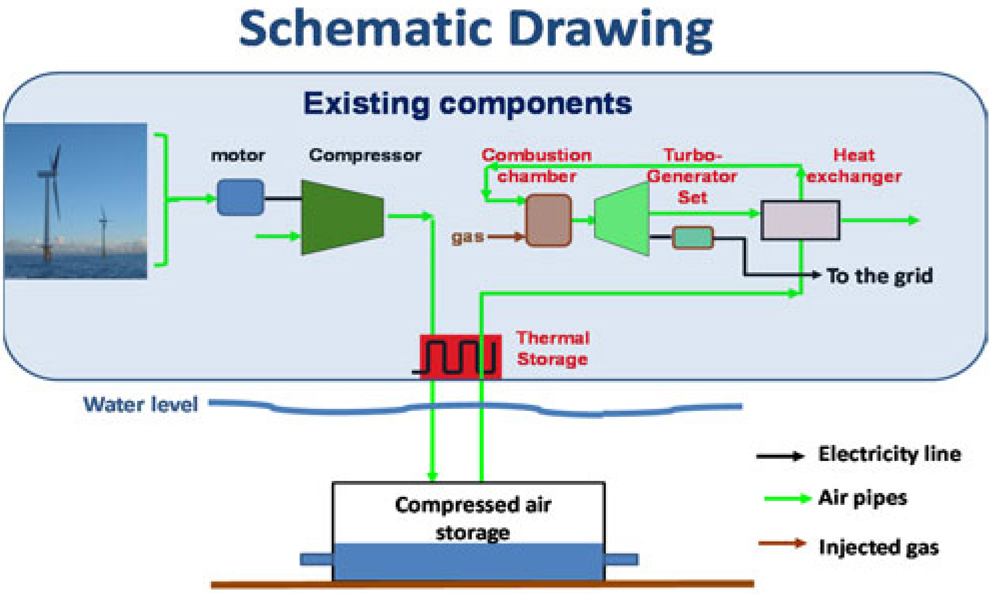

Figure 29: Compressed air energy storage [72]

When CAES is placed offshore, the hydrostatic pressure can be used as main force. This has significant advantages:

- Constant system pressure (not depending on amount of air stored)
- Very simple air container possible (underwater balloon)

Such an underwater balloon as container (fixed pressure, variable volume) would be able to store twice the amount of energy as a comparable solid container (fixed volume, variable pressure), due to the constant pressure property.

Another advantage of offshore CAES is that the compression and expansion machinery can be placed above the water surface, which simplifies design and maintenance. Of course, the machinery would have to be placed on a platform or other structure. This increases the losses in the pipes going to the storage device. Yet, the gain of not having the machinery subsea might make up for the efficiency decrease.

However, the stored energy is a function of both volume and pressure. Offshore wind power plants are usually built in shallow waters (less than 50m depth), where the pressure is up to 5 bar. The required air storage volumes would be enormous at this low pressure. Pressure levels considered for CAES are usually at least an order of magnitude higher. Also the buoyancy of large subsea air storage volumes is a problem, leading to expensive anchoring solutions.

High hydrostatic pressure (50+ bar) can in the North Sea only be found in the deep waters of the Norwegian Trench. It also exists close to the North Sea at the northern coast of Scotland. However, in these deep water regions, there are no concrete plans for wind power plants, also due to the water depth. Deep water CEAS and shallow water wind power plants would therefore have to be installed with some distance in between, demanding for more transmission infrastructure (within the North Sea) than a geographically concentrated solution. Although there are plans for wind expansion in Northern Scotland, there is large uncertainty in the deployment of offshore wind farms. However, in future scenarios installation of deep water offshore wind power plants and nearby CAES plants can be more viable.

There is ongoing research at the University of Nottingham in the UK on underwater CAES solutions. Also, a Canadian company, Hydrostor inc., has since the summer 2014 been operating a prototype CAES plant outside Toronto. The company is in the process of commercialising the technology, and has already signed a contract on delivering such a solution to the grid operator on Aruba, an island off the coast of Venezuela. Of the two offshore storage technologies it seems that CAES is the most developed.

2.6.2. Pumped Hydroelectric Energy Storage

Pumped hydroelectric energy storage is a bidirectional implementation of a hydroelectric power plant. It is based on water exchange under hydrostatic pressure difference between a lower and an upper reservoir (shown in Figure 30). The main advantages are the low cost of energy and the possibility of frequency regulation. This is the only electric energy storage technology that is implemented in large scale and that can be considered mature.

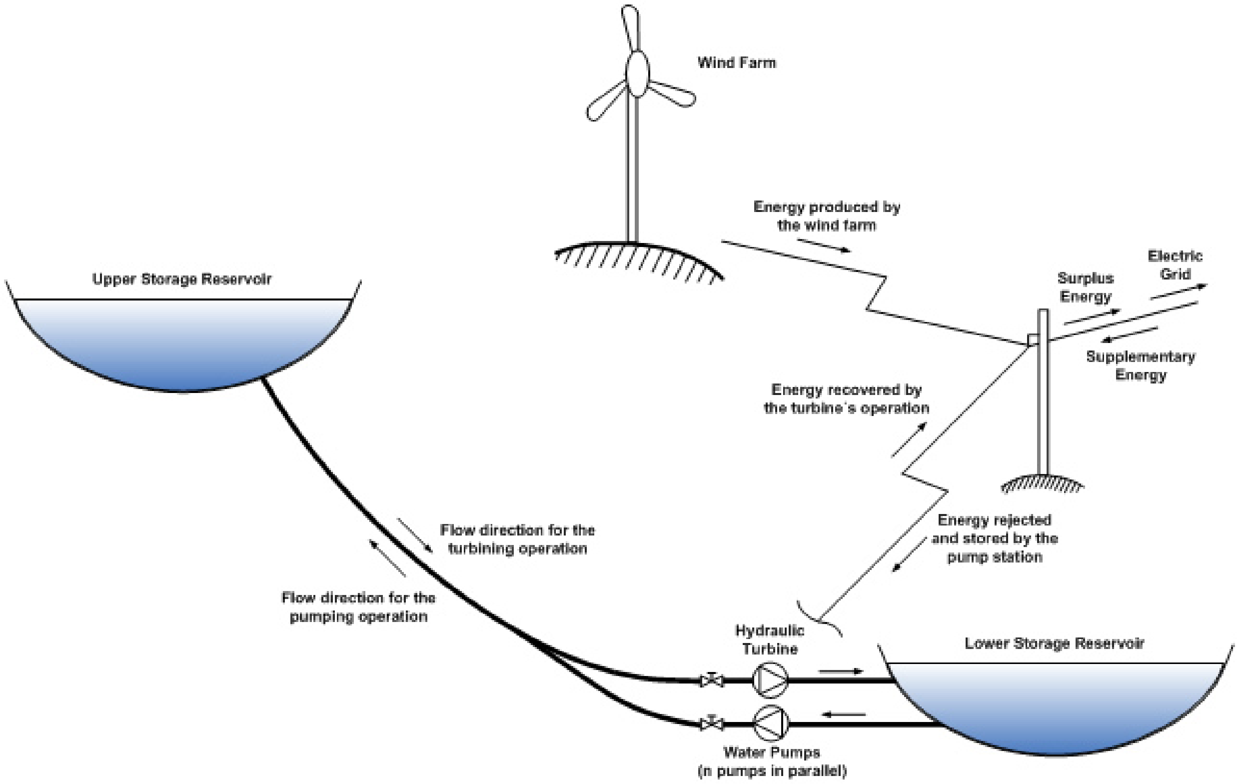

Figure 30: Pumped hydroelectric energy storage with wind power [73]

Offshore pumped hydroelectric energy storage would need an artificial reservoir at the sea bed, which is held at about atmospheric pressure. This (lower) reservoir would exchange water with the surrounding sea which forms the upper reservoir. For this concept, the turbine and auxiliary machinery has to be placed subsea, which leads to a complex system.

The stored energy is a function of both volume and pressure. Identical to the CAES, this will favour deep water locations for higher pressures, like the Norwegian Trench. Concrete spheres were proposed as subsea storage containers [74].

Two parameters must be solved for any storage device placed underwater, buoyancy and wall thickness to withstand the water pressure. The buoyancy of an empty (air filled) subsea container can be compensated by choosing a solid concrete construction with sufficient mass and therefore weight. Such a solid construction would also be able to withstand high pressures. A sphere-shaped pressure tank would be the optimal geometry (but it might be difficult to manufacture).

For a given water depth (setting the minimal wall thickness to withstand the pressure), there is a minimal sphere radius to fully utilise the concrete used. Smaller spheres would be heavier than necessary not to float. Larger spheres would need to increase wall thickness to add mass.

For a given sphere radius (setting the minimal wall thickness to counteract buoyancy), there is a minimal water depth to fully utilise the concrete used. In shallower water, the pressure tank would be stronger than necessary to withstand the pressure. In deeper water, the wall thickness would need to be increased to withstand the pressure.

This implies that there is a "sweet spot" (actually a "sweet line") where the pressure tank's wall thickness requirements from buoyancy and pressure are the same, leading to one "optimal" wall thickness.

For smaller sizes the sweet spot goes to shallower waters while larger sizes towards deeper waters. There is a linear relationship between optimal water depth and reservoir dimension or radius, indicating that at double water depth, the pressure tank should have double radius (eight-times the volume). Seen as stored energy increases with depth, this concept favours the latter in combination with large spheres. The concept of the sweet spot is visualised in Figure 31.

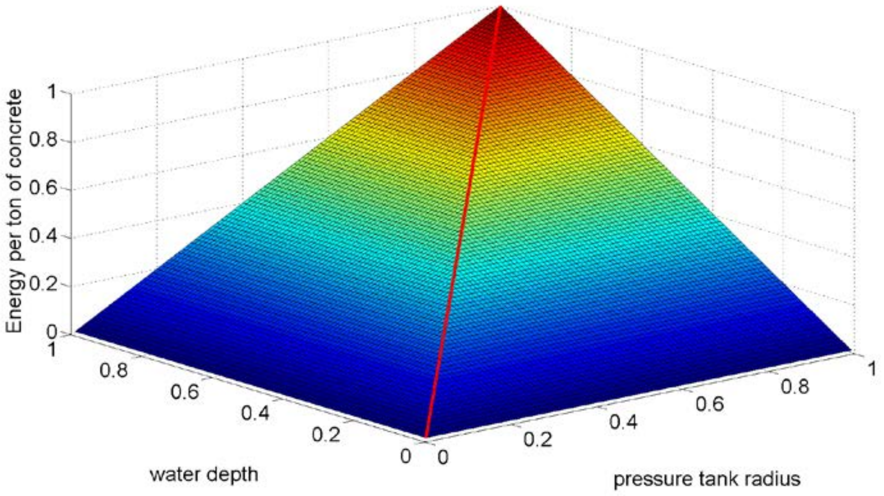

Figure 31: Visualisation of the sweet spot

In an application view, larger containers would allow for exploiting economy of scale up to a certain practical limit. For the case of the Northern Sea, most of the area is shallow and would necessitate many smaller containers to achieve a large energy storage potential at low pressure. This, however, would lead to tremendous amounts of concrete needed, raising the question if such an approach can ever be cost efficient.

An alternative solution to concrete spheres at the sea bed is a concept from called an Energy Island [75]. This concept is currently being studied in Belgium by Belgian grid operator Elia. This concept does not utilise containers at the sea bed, but it is more similar to regular onshore pumped hydroelectric facilities, with an upper and a lower reservoir in open air. In a large body of water like the sea or lake, a circular dam is made from the sea bed and up above the water surface forming a ring shaped island. The trapped water body inside the island can now be pumped out and create a net head. The upper reservoir is in this case the surrounding sea, while the lower reservoir is an artificial saltwater-basin in the centre of the ring shaped energy island.

Figure 32: Energy island [75]

If the energy island is considered ring shaped with a constant depth, then stored water would increase quadratically with the radius while the length dam needed to surround the water column is only proportional to the radius. Thus, this concept also favours larger installations.

Regarding the feasibility of use in the North Sea offshore grid, several aspects should be considered. Using the sea bed sediment to build the dam would probably improve project economy, as an alternative to transporting material from land. Therefore suitable areas of the North Sea should be identified. The human capacity regarding dam construction is available in Europe, particularly in the Netherlands, which is one of the connecting countries of the offshore grid. However, studies must be done regarding the impacts on the surrounding ecosystem. A large area would cut off and be unavailable to current marine life.

3. Offshore Network Systems Aspects

The future NSSG will need more than only components with satisfactory performance. A grid will need systems that coordinate the large number of widespread components. Control systems and protection systems are the most prominent ones, and these are treated in this section.

3.1. Control Systems for MT-HVDC Systems

The control system of a DC grid can be seen as consisting of three parts, similar to AC system control with primary, secondary and tertiary control [76].

DC/AC grid system control is the slowest controller. Its task is to determine the system flow based on the planned schedules. It can be compared with tertiary control in AC systems. The current injections into and out-of DC grids are completely regulated by the power converters. However, in a meshed grid the flows on each line cannot be controlled directly and are determined by the voltage at the nodes. As the flow at each line is not controlled, congestions may occur in a DC grid. So, precise and automated control of node voltages enables possibilities for indirect flow control. The possibilities are however more limited as compared to AC, due to the absence of reactive power.

Coordinated system control can be compared with secondary frequency control in AC systems. Its task is to move the system from the stable post-disturbance state back to the original state (if possible) or to an alternative system state which is desired. It acts slow enough not to interfere with system dynamics.

Node voltage control is referred to as fastest DC grid control system (similar to primary frequency control in AC systems). The balance indicator for a DC system is the DC voltage (similar to AC frequency in AC systems). A disturbance of the current balance will result into a rising or falling DC system voltage. The task of node voltage control is to stop the voltage deviation within the boundaries, but not necessarily to re-establish the normal voltage value. It establishes a stable post-disturbance state. Node voltage control is mostly considered to be a local control without communication, but also communication based concepts have been proposed. In the operation of MT-HVDC system, one of the most critical issues is to keep the current balance via the voltage control [77]. Several methods to balance the currents and control the voltage have been studied in the literature.

Node voltage control is a HVDC converter control system and not a DC grid control system. A variety of DC grid control systems can be composed from the different converter control systems. The description of the MT-HVDC control systems presented here is mostly based on [78].

3.1.1. Converter Control Strategies

Many of the proposed control methods share the general concept that they are defined by a linear or piecewise linear control relationship between converter DC voltage and converter DC flow. DC flow is used as a general term including both current and power. The control strategies establish either a voltage-current relationship or a voltage-power relationship. The linear strategies are referred to as basic strategies and the piecewise linear strategies as advanced strategies.

Basic Converter Control Strategies

The control curve of the linear strategies has only one segment, which applies for all operation. The main linear control concepts are:

- Constant voltage control
- Constant flow control
- Droop control

Voltage droop control creates a proportional relationship between the voltage and the control base (current or power). It works as a simple P-controller. When a contingency occurs (deviation of the measured voltage), the droop control is characterised by a proportional steady-state deviation of the current or power reference as a result of the proportional control action.

Constant voltage control and constant flow control can be seen as extreme cases of droop control where the slope of the relationship becomes zero and respectively infinity.

Advanced Converter Control Strategies

The piecewise linear control curves usually have three segments, where the inner segment represents normal operation and the two outer segments represent disturbed operation. Examples of piecewise linear control strategies are:

- Voltage margin control
- Dead-band droop control
- Autonomous converter control

The control behaviour within a segment is identical to a basic converter control strategy, and it can be expressed with a single parameter: The slope of the relationship, called the droop constant.

The advanced strategies with three segments usually have two different droop constants: one for the slope during normal operation, and one for the outer segments for disturbed operation. The linear control strategies could be seen as a special case of the advanced control strategies, where these two parameters are identical.

Usually, the advanced controller is more active for disturbed operation, taking action with a higher control gain than for normal operation. This is due to need to support the voltage well during a disturbance.

General Converter Control Concept

A general control concept called undead-band droop control has been defined, as a general piecewise linear control concept with two degrees of freedom [79], [80]. It includes all the other six mentioned methods as special cases of undead-band droop control. It also allows for any kind of combinations of the other control strategies.

3.1.2. Grid Control Strategies

The two types of converter control strategies lead also to two general types of grid control strategies:

- Basic grid control strategies
- Advanced grid control strategies

Basic Grid Control Strategies

The basic strategies can be sub-divided into two strategies:

- Centralised voltage control
- Distributed voltage control

Centralised voltage control means that one terminal controls the DC voltage (zero droop). All other terminals control their flow (infinite droop). This strategy is not suitable for larger systems, as it does not support N-1 reliability due to the dependence on the one voltage controlling terminal.

Distributed voltage control is based on droop controlled converters. This method is inspired by AC system operation, where it has proven good reliable performance in more than a century. It is very well suitable for large systems.

Advanced Grid Control Strategies

The advanced strategies can be sub-divided into three strategies:

- Centralised voltage control with centralised back-up
- Centralised voltage control with distributed back-up
- Distributed voltage control with distributed back-up

Centralised voltage control with centralised back-up is based on voltage margin control. There is a single converter controlling the DC voltage, but in case of failure, another dedicated single converter will take over the task. The size of system where this strategy can be usefully applied is larger than for centralised voltage control without back-up. However, it is not suitable for large systems, where disturbances can occur, which can be hard to handle with single converters.

Centralised voltage control with distributed back-up is based on dead-band droop control. A single converter controls the DC voltage in normal operation, but in case of a disturbance several or all other converters take action to stabilise the DC voltage. This system can handle larger disturbances than a centralised back-up, but again, in is not suitable for the largest systems, where any single converter is insignificant compared to the total system. In such a system, the single voltage controlling converter would be overloaded trying to control the very large system, leading to frequent "disturbances" caused by the controlling converter reaching the limitations.

Distributed voltage control with distributed back-up is based on undead-band droop control. Like regular droop control, this is suitable for any size of system. However, it adds the possibility to react towards disturbances by a dedicated control parameter for disturbed operation.

3.2. Protection Systems

Power system protection is a topic that has been extensively investigated for more than one century [81]. However, this extensive knowledge is limited to AC systems; DC power system protection is still under development. Well known principles from AC protection can often not be applied directly to DC systems. The DC protection equipment has been treated in Section 2.4, and the system aspects are treated here.

The protection system is one of the major challenges for large HVDC systems [82]. There are several reasons why DC protection is very challenging compared to AC:

- DC current has no zero crossings
    - It is difficult to interrupt DC current
- In DC systems, the concept of impedance does not exist
    - Short circuit current level limited only by resistance
        - High short circuit current levels
        - Large area affected by short circuit
    - Inductance only reduces di/dt
- DC systems have small time constants
    - Very fast protection necessary
- Several VSC HVDC converter topologies have anti-parallel diodes
    - Vulnerable to DC faults

Fault Detection and Localisation Methods

When a fault occurs, the DC voltage drops in the entire HVDC system. The protection system must identify and isolate the fault location, preferably based on local measurements [83].

There are many fault detection and localisation methods that may be used for DC grids which are based on AC protection schemes. The most promising solutions for detection methods are based on the travelling wave principle, because it is one of the fastest and most accurate detection schemes. However, this method requires measurements of arrival time of the front-wave generated when the fault occurs, so the method depends on high sampling frequency devices. Moreover, the accuracy of the method highly depends on the parameters of the line and is vulnerable to interface signals.

Other detection methods typical for AC systems may be not suitable for DC grids. For example overcurrent-based schemes lack of selectivity [84], differential protections are totally dependent of a reliable telecommunication system, [85, 86], or impedance-based schemes that are unfeasible since no fundamental frequency is defined during fault transients [87].

For location methods there are a few options in literature [83, 88]. Some of them are based on signal processing methods such as the Wavelet-based protection method proposed in [83]. Wavelet-based protection scheme may use the voltage wavelet coefficients, the current wavelet coefficient, or both. In this method, based on the wavelet coefficient in each line, the fault is detected when a coefficient overpasses the specified threshold value [83].

There are methods based on the distributed parameters which use transmission line models to estimate the fault distance. However, these methods require a lot of computation time [88]. Also artificial neural networks (ANN) have been proposed to detect and to locate fault at DC grids, but it requires a learning process which can be very slow.

3.3. System Interactions

Even if all components of a system are in place and working as desired, system wide challenges might still arise. This is mainly caused by utilising model simplifications, which later prove to have neglected crucial aspects.

Real-life systems are basically never completely linear, and all modelling always comprises simplifications. While simplifying, it is important to not disregard aspects what are relevant for system behaviour. It can however be difficult to always know in advance what will be relevant and what not.

Power system control (and any other system control) is often treating a linearised version of the real non-linear system. Successful operation of the electricity system has been achieved for more than a century. However, a large share of new non-linear components in an electrical system (power converters) can produce unexpected interactions with potential impact on the overall reliability.

Furthermore, the North Sea Super Grid is expected to be exposed to more severe conditions than traditional transmission grids due to the stochastic power generation of the dominant sustainable energy sources (offshore wind power plants), the large converter loads (oil&gas platforms and onshore HVDC stations) and the presence of long cables. These factors can trigger resonances and non-linear interactions between the components that can range from minor harmonic generation to severe instabilities. These effects should not be neglected in an offshore grid due to the large costs and the complex maintenance.

3.4. Standardisation

The deployment of a full scale NSSG for the grid connection of the first pioneering offshore projects cannot be justified or financed. Individual projects are therefore coordinated one by one at the moment, and they do not necessarily follow an internationally agreed master plan. The individual approach is logical, but will lead to complication in the future, when these systems are to be interconnected.

There is currently a limited number of big manufactures of HVDC converters. Most of the operational VSC HVDC projects have been developed by ABB, but Siemens and Alstom Grid are catching up with many projects, of which few are operational but several under construction. These three manufacturers have their own system design, and multi-vendor compatibility has not been prioritised.

There are also activities in China, but it seems that there is little coupling between the Chinese and the European activities. It is also difficult to find information on the Chinese VSC HVDC projects.

Nowadays, HVDC systems are mostly point-to-point schemes, and they are individually optimised to maximize the return on investment of the stakeholders. Due to the relatively small number of HVDC projects and the large size of the projects, individual planning is beneficial and expected benefits from standardisation are small.

The implementation of HVDC grids like the NSSG will significantly change this approach. Any grid must be flexible and expandable, and it can therefore not be locked to a specific supplier. Multi-vendor compatibility is therefore crucial, and to achieve that, standards will be needed.

However, defining valuable standards for immature technologies is very challenging. Too much standardisation could be an obstacle to the development of technology. For this reason, the parameters to be standardised should be chosen carefully. It is important to remark that too much standardisation could lead to stranded assets if current installations were rendered obsolete [89].

This mentioned challenges with standardisation imply an iterative process with intermediate steps and temporary guidelines, which eventually can lead to standards.

DC Voltage

The most important technical parameter of an HVDC system is probably the transmission voltage. Several different voltages have been selected for recent XLPE cable based HVDC projects:

- ±150 kV
- ±200 kV
- ±250 kV
- ±300 kV
- ±320 kV

Especially 320 kV has been popular in the last years, and it can be seen as a first unofficial "standard". This choice has been based on limitations of available XLPE cables. However, the European plans for a super grid, which can transfer significantly more power than regular 380 kV AC can, indicate that higher DC voltages are needed. Also the NSSG would significantly benefit from higher voltages.

In August 2014, ABB released a new XLPE-cable with a voltage rating of 525 kV [15], which most likely will undermine the 320 kV "standard". This newly developed cable boosted possibilities and expectations significantly. If it can prove successful performance in practical applications, it has the potential to be a game changer for super grids. It could even set a new 525 kV voltage standard. This is however only possible if these new cables are available for competitive prices and without production bottlenecks.

The establishment of a 525 kV standard could be again be undermined by new cables with higher voltage ratings. Prysmian offers MI cables up to 600 kV [12], but there seem to be manufacturing difficulties. With reaching 525 kV, XLPE has reached similar voltage levels as other HVDC cables (MI and SCFF).

800 kV has also been applied in HVDC projects, but this is limited to overhead lines at the moment. It seems difficult to forecast if and when 800 kV cables might become available. Without cables, the applicability of 800 kV in Europe can be questioned, due to the current focus on the North Sea region. This high voltage would also allow for ca. 2 GW of power on a single cable. It is not clear that such a high power on a single cable is actually desired, since it raises system reliability concerns. It would most likely need upward adjustment of the primary reserve requirements.

Concerning future DC voltage standards, 320-525-800 kV seems reasonable also regarding the difference between the voltage levels (roughly 60 % increase from level to level).

AC Frequency

The standardisation of AC voltage for connecting offshore wind power plants and oil&gas platforms to clusters is not a major concern, due to the availability of AC transformers. However AC frequency might pose a challenge, because both 50 Hz and 60 Hz are used in the North Sea.

Most offshore wind turbines are made by German and Danish manufacturers. As these designs to some extend are based on onshore wind turbines, it is natural that they would operate at the European frequency of 50Hz. In the oil&gas industry however, a lot of know-how and technology came from the USA, leading also to platforms in the North Sea with internal grids operated at 60 Hz.

A synchronous interconnection of both 50 Hz and 60 Hz systems to form a cluster is not possible. An AC-AC frequency converter could of course connect 50 Hz and 60 Hz systems, but this would require dedicated expensive hardware. A more natural approach seems to be indirect connection through connections to the same DC system through AC-DC converters.

Control Systems

Although different manufactures might develop different control algorithms, they will be eventually connected to common systems and they should operate together. The control parameters should not differ significantly. For instance, if ramping speed on the different converters differ too much, unwanted dynamics may occur such as resonances or oscillations.

Protection Systems

This is a very critical issue in DC grids; so many aspects of the protection system must be standardised such as thresholds to separate the normal transients to fault condition, maximum short circuit current of converter station, maximum time to detect a fault condition, fault clearing mechanisms, location of fault clearing devices, etc.

Communication Systems

Communication protocols must be standardized in order to share the same communication to all converters. This could be problematic when existing HVDC systems, with existing non-standard protocols are to be interconnected.

Support Schemes

This is not a technical aspect, but it has significant impact on the technical solutions for the NSSG. Differences between the North Sea countries regarding feed in tariffs will create the incentive to direct the produced power in a direction that might not be useful from a system operation point of view. This can lead to additional bottlenecks and losses. Standardisation regarding offshore wind power support schemes is therefore important.

3.5. System Layout Optimisation Challenges

As mentioned before, the NSSG will consist of both AC and DC technology. There are a variety of possibilities where and how the interfaces between AC and DC can be implemented, leading a very large number of possible options. This can pose challenges for grid optimisation calculations.

Considering two AC stations with DC connection, there is only one possible topology: a point-to-point DC connection between the two stations.

Considering three AC stations to be connected, it is already possible to do this with two or three point-to-point links, with three- or four-terminal links, possibly with meshes and also other combinations. There are a total of 14 possible topologies considering only AC-DC converters. A simple graphic illustration of these 14 possibilities to connect three points is given in Figure 33. If DC-DC converters are also considered, the number of possibilities increases from 14 to 76.

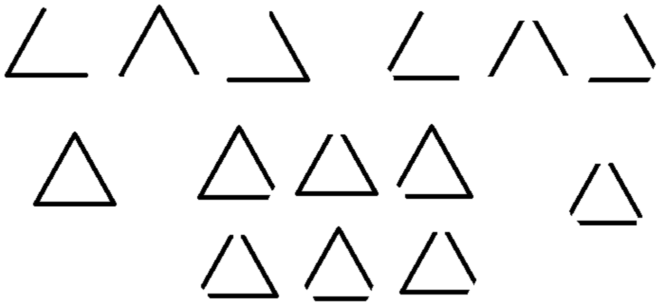

Figure 33: The 14 possibilities to connect three points

Considering four AC stations already leads to more than a thousand possibilities, and five AC stations to more than a million possibilities when applying only AC-DC converters. These numbers again become much larger when also considering DC-DC converters.

The future NSSG will likely connect significantly more than five AC stations. These numbers clearly indicate the impossibility to consider "all possible solutions" for a DC grid in the planning process, not even with specialised algorithms and large computational resources.

4. Conclusions

The conclusions of this report are split into two parts, where the first on is summarising the report in form of a gap analysis, while the second is proposing ways forward towards the implementation of a North Sea Super Grid.

4.1. Gap Analysis

The gap analysis consists of three parts, addressing knowledge gaps to be closed by research, technology gaps to be closed be development and experience gaps to be closed by demonstration projects.

An attempt has been made to classify all the subjects on the Technology Readiness Level (TRL) scale. This is however challenging, since it is not specific technological items, that can be precisely rated, but it is rather categories of technology that contain a variety of specific items, which are at different TRLs. Another problem with the ratings is related to the massive investment costs of full scale HVDC installations, which prevent the construction of a full-scale prototype, even though the technology is believed to be ready. The TRL ratings in this section can therefore only be taken as a guideline.

4.1.1. Knowledge - Research

This section summarises different subjects of interest for a future North Sea Super Grid, where basic research is still needed.

Subsea Installations

(Estimated TRL: 2-5, treated in Section 2.5.3)

The electrical installations for offshore wind power plants are currently built above sea level. The necessary substructure for a transformer or converter platform becomes more costly with increasing water depth and mass. Subsea technology is under development for the oil&gas sector, to enable more efficient solutions for deep waters. The main challenges are the hydrostatic pressure, the rough sea environment and the extreme reliability requirements, as maintenance is very complicated at the seabed.

Subsea technology has not been seen as crucially important for offshore wind, where water depths are usually less than 50m. However, once these emerging technologies have gained maturity and are available for competitive prices, they might find its way into the offshore wind sector, possibly leading to transformer stations or even converter stations being placed on the sea bed. The possibilities and potentials of the subsea approach should be investigated.

Hybrid AC+DC Grid Control

(Estimated TRL: 1-3, treated in Section 3.1)

The electrical power grid is today considered to be an AC grid, while the integrated HVDC systems are treated in a separate way. With the steadily increasing share of HVDC components in the European power grid, this approach is becoming outdated. Control philosophies for hybrid AC+DC grids have to developed, as these can address the future reality much better than the classical AC approach. Done correctly, this can significantly increase the overall reliability, or reduce the cost while maintaining the same level of reliability.

On the one hand, the North Sea region with its very high concentration of HVDC infrastructure is a perfect case for studying hybrid AC+DC grid control. On the other hand, the North Sea region will significantly benefit from improved operational principles.

DC Protection Systems

(Estimated TRL: 1-5, treated in Section 3.2)

Protection for large HVDC systems is challenging. Protection schemes including fast fault location for selective fault clearing are still work in progress. There are basically two approaches: Adapting AC protection strategies to work for DC (TRL3-5) or completely new DC power system protection (TRL 1-3).

The traditional AC philosophy could be stated as 'if there is a short circuit, the faulty component has to be isolated from the rest of the system before system stability is lost'. However, this is very challenging and costly to realise for DC systems. The protection components, both circuit breakers and fault current limiters are immature at the moment. Although HVDC breaker prototypes have been successfully developed, the performance has never been tested in a real HVDC system. Also fault current limiters are still at an early stage of development. The optimal HVDC converter control in case of a dc fault is not yet known, and possibly depending on converter topology.

The design of the complex protection system needs further development. This subject is currently addressed within the BestPaths project, but it is unlikely that all questions will be answered within that project.

The fast time constants of DC systems (ms-range) in combination with the often very long HVDC cables (hundreds of kilometres) have the consequence that hard physical limits are hit regarding communication for protection coordination, due to the finite speed of light. This demands new approaches compared to AC protection, that rely less on communication.

New alternative protection concepts should therefore be investigated and compared to the classical AC-inspired protection approaches. One idea is to section a large HVDC grid into several smaller independent HVDC systems, where none of these subsystems is crucial for overall grid integrity and electricity customer reliability. Another option would be to shut down, reconfigure and repower a large HVDC system in case of a short circuit quickly enough, that the temporary outage does not severely influence the connected AC grids or the customers, similar to a low-voltage-ride-through event.

Low Frequency AC Transmission

(Estimated TRL: 9 for trains, 1-2 for offshore wind, treated in Section 1.2)

Low Frequency AC (LFAC) technology has to be studied with regards to its use for integrating medium-distance offshore wind power plants. For near-shore WPPs (less than ca. 100 km from shore), regular AC is the normally the best choice, and for remote offshore WPPs (more than ca. 100 km from shore) DC is usually the best choice. However for WPPs with an intermediate distance (ca. 50-150 km from shore) LFAC might offer benefits.

However, the LFAC approach is also posing a serious threat for the establishment of a future North Sea Super Grid, as it pushes the limits of how far offshore we can go with AC technology. If many of the future offshore wind power plants will be integrated with LFAC instead of HVDC, the number of HVDC connected facilities is reduced. A smaller total number of relevant facilities might reduce the incentives and benefits to considerer a HVDC based North Sea Super Grid.

Isolated Offshore AC Systems

(Estimated TRL: 2-8, treated in Section 1.2)

Operating and controlling (HVDC connected) isolated offshore AC systems is challenging. These are highly important for offshore supernodes, and can therefore be an enabler for the NSSG. The consideration of such AC systems is rather a new phenomenon. This is why the knowledge and experience base is still insufficient at the moment.

Since rotating inertia of electrical machines significantly contributes to slow down the dynamics of the power balance in an AC system, it is difficult to handle AC systems with low inertia. Power electronics do not provide inertia as machines do, leading to much faster system dynamics, imposing tougher control system requirements.

Isolated offshore AC grids are typical examples of low inertia AC grids. There is a low (or possibly zero) inertia AC system in operation at the Bard Offshore 1 wind power plant. This system is experiencing significant problems, so even though the technology has reached real-life application, there is still basic research ongoing to better understand and handle the dynamics of low inertia AC systems.

Another problem associated with isolated offshore AC systems is related to harmonic distortion. In a system where all sources and sinks are switched power converters which produce harmonics, distortion levels can reach problematic values if the harmonic aspects are not taken seriously enough.

Value of Offshore Electric Energy Storage

(TRL not defined, since it is not a technology)

Present offshore grid studies have focused on grid topologies and detailed cable planning. However, integrated storage has not been considered enough in this context. Research is needed on the added value of placing storage units offshore, especially considering placement in a meshed grid HVDC structure. This would further identify the potential of offshore storage in competition with similar onshore storage solutions.

In the North Sea region with its shallow waters and low hydrostatic pressure, it is not clear yet, if offshore storage is competitive compared to transmission to land and onshore storage. Therefore the costs and benefits of offshore storage have to be investigated. This investigation should go hand in hand with the development of offshore storage technology (Section 4.1.2), as the immature state of the technology is at the moment putting severe uncertainty on cost estimates.

4.1.2. Technology - Development

This section summarises different subjects of interest for a future North Sea Super Grid, where already developed principles have to be developed further into physical devices.

DC Fault Current Limiters

(Estimated TRL: 2-5, treated in Section 2.4.2)

A short circuit in a DC system leads to a high discharge current fed by the total system capacitance. Both the fast rise time of the fault current as well as the total amplitude pose significant threats to the system and its components. There is a variety of different concepts how the fault currents can be reduced, and these have to be investigated and tested, towards applicable devices to be used in future DC grids.

DC Circuit Breakers

(Estimated TRL: 3-6, treated in Section 2.4.1)

There have been a few demonstrators of DC circuit breakers at reduced voltage rating, which successfully have delivered a proof of concept, but further development is still needed before DC circuit breakers are an available and certified product on the market. At the moment there is not even a specification for DC circuit breakers, so certification is not possible.

High Power DC-DC Converters

(Estimated TRL: 3-5, treated in Section 2.3)

DC-DC converters have existed for many years and the academic community has come up with an almost infinite number of different topologies for DC-DC power conversion. However, these have mostly been studied in simulation or low-power laboratory set-ups. Adaptation to higher voltage and current levels is necessary to address the final target of DC-DC converters in the same gigawatt power range as AC-DC converters.

The invention of the AC transformer was the one main factor, which determined that all power systems worldwide operate with AC and not with DC. An equivalent power-electronic 'DC transformer' with similar power levels would be a game changer, eventually putting DC into a generally advantageous position over AC, and it would be extremely valuable for all future HVDC grids, not only in the North Sea.

Offshore Storage Technology

(Estimated TRL: 2-7, treated in Section 2.6)

An underwater Compressed Air Energy Storage (CAES) prototype is currently operating in a real application situation. Several other concepts are also being followed up, some in prototype stage, while others in concept stage. As the field of technology has seen little activity historically, there is still a lot to be done.

Offshore Platforms and Foundations

(Estimated TRL: 6-9, treated in Section 2.5)

The construction of offshore platforms and its foundations is very costly. This is significantly increasing the cost of offshore HVDC compared to onshore HVDC. With only a few of such systems installed world-wide, it seems likely that the design still has a lot of room for improvements. Reduction of size and weight can significantly reduce the cost. This has to be addressed to increase the economic viability of offshore HVDC.

4.1.3. Experience - Demonstration

It would be a very large step to take the decision to now build a full scale North Sea Super Grid. Intermediate steps on the way towards the DC super grid would be very important. There are generally two possible ways to approach the full scale DC super grid, and both should be pursued simultaneously.

Medium-Voltage DC Wind Power Plant Collection System

(Estimated TRL: 2-5)

One approach would be to start from existing complex DC systems at low voltage and power, and to scale up the ratings. A natural step on this path would be a demonstration project with a DC collection system for a wind power plant. This has been studied in academia, but to date there are (to our knowledge) no concrete plants to realise such a wind power plant collection system. It would be beneficial to gain experience with complex multi-terminal DC systems at medium voltage before going to high voltage.

Multi-Terminal HVDC System

(Estimated TRL: 8-9 China, 4-7 Europe)

The other approach would be to start from existing full-ratings simple two-terminal HVDC systems, and to increase complexity, by implementing at least one additional terminal.

Until now no one was willing to take the risk to construct a first multi-terminal HVDC system offshore (like the discarded Krieger's Flak project in the Baltic Sea). Also all ideas for T-in connections of offshore wind power plants in the North Sea onto HVDC interconnectors have not been followed up. The NordLink cable from Norway to Germany would have been an excellent project for this, as the cable is passing offshore wind power plants on its route. However, it seems not possible to realise such a demonstrator with the specific NordLink project due to a lack of interest from the relevant stakeholders. The situation is similar regarding other HVDC interconnector projects (e.g. COBRA).

It could also be possible to first gain experience with multi-terminal HVDC systems onshore before taking it offshore. However, until now all project proposals regarding onshore multi-terminal HVDC have been discarded. A missed opportunity for a multi-terminal system is the 'HGÜ-Trasse A' in western Germany, where multi-terminal properties actually are essential for the project. However, at the moment the planning is considering two independent two-terminal HVDC systems, which are connected by a 'supernode' through AC. Also the South-West HVDC Link in Sweden has been cancelled in its original multi-terminal topology.

There is one onshore three-terminal HVDC in operation (SACOI, Italy and France), but this is not based on voltage source converter (VSC) technology. It can therefore not really be seen as a step towards a future VSC-based meshed HVDC grid.

The Caithness Moray link in Scotland [23], [30] will be constructed as a two-terminal link, but it is designed for multi-terminal capability. The two terminals will not have the same power rating (1200 MW and 800 MW), so the larger terminal has 400 MW of extra capacity, which cannot be utilised in the regular two-terminal setup. The additional 400 MW only become useful if the third terminal will be realised in Shetland. Investing in these extra 400 MW shows a serious interest to actually upgrade to a multi-terminal arrangement later, because otherwise it would be a stranded investment. However, even though the third terminal seems likely to be realised, there is no confirmation, and it could be postponed for years.

So the game is still open, and time is running out to find a future project for multi-terminal HVDC demonstration in Europe, to start catching up with China, where already two such systems are in operation.

4.2. Ways Forward

This section is summarising what the different stakeholders need to do, to make progress on the realisation of the North Sea Super Grid.

4.2.1. Research Community

The research community has actively addressed many relevant subjects regarding future North Sea Super Grid. However, the remaining knowledge gaps mentioned in this chapter have to be addressed:

- Subsea installations
- Hybrid AC+DC grid control
- DC protection systems
- Low frequency AC transmission
- Isolated offshore AC systems
- Value of offshore electric energy storage

A continuation of the strong research efforts or even an increase of the activities would be very useful. The concepts developed in research can provide indications in which directions the development of new technologies should move on.

4.2.2. Manufacturers

The HVDC manufacturers have actively contributed to the development of the necessary components for a North Sea Super Grid. A few examples to highlight would be the introduction of multi-level VSC HVDC converters by Siemens or the development of the hybrid HVDC circuit breaker by ABB. Alstom Grid has entered this market sector later and is catching up quickly. They have investigated many new possibilities for HVDC converter topologies and also a concept for DC power flow controlling devices. Having a third supplier and competitor in the market also significantly improves the component supply situation for HVDC grids.

It would be very important if the manufacturers continue to invest in technology development, especially with focus on the technology gaps mentioned in this chapter:

- DC fault current limiters
- DC circuit breakers
- High power DC-DC converters
- Offshore storage technology
- Offshore platforms and foundations

To make this happening, it is crucial that the manufacturers receive interest from the potential future customers of those technologies (mainly TSOs and offshore wind power plant developers).

4.2.3. TSOs and offshore wind power plant developers

A lot of progress has been made with regards to offshore HVDC. Many offshore HVDC systems have been installed and are being installed at the moment in the German section of the North Sea under the lead of TenneT. This is a major enabler for a future North Sea Super Grid, as valuable experience is being gained and a lot of important lessons are being learned at the moment. TenneT can clearly be seen as the world leader in offshore HVDC.

These offshore HVDC installations have proven to be costly even if standard two-terminal schemes are realised. The construction of offshore HVDC converters on platforms has been a major challenge, which ended up being more complicated than expected. These unexpected challenges that led to significant delays and extra cost were due to both a lack of experience with offshore operations and also due to electrical engineering problems with harmonics (experienced at the Bard Offshore 1 wind power plant, leading to significant down times of the wind power plant) [90],[91],[92],[93],[94].

However, the TSOs still have to become more active regarding multi-terminal HVDC. With the lessons learned from today's offshore two-terminal HVDC projects, the implementation of a multi-terminal offshore HVDC system should be addressed as a next step.

For Europe as a leader in HVDC technology, it is unfortunate, that nothing has happened so far regarding multi-terminal HVDC. While important experience is gained today regarding offshore HVDC, multi-terminal HVDC is still standing still. There is only the Caithness Moray link project [23],[30] to be implemented as a two-terminal system by 2018, which has the option to upgrade to three-terminal later on.

Here Europe as a whole has lost a competitive advantage towards China, where two multi-terminal schemes are in operation. This lost opportunity gives China a head start, which will be difficult to catch up, and which will become more and more difficult with every day passing and Europe not even getting started.

Grid enhancements are mainly assessed by the TSOs with regards to cost effectiveness, risk reduction, quick implementability and general reliability. This conservative approach favours proven technology. However, bringing forwards new innovation is always associated with extra cost and risk. Here the European decision making process, which is very different compared to China, is aiming to prevent risk, but this at the cost of a slower progress. It would be highly important that the TSOs get involved in the two major demonstration projects that are still missing:

- Medium-voltage DC wind power plant collection system
- Multi-terminal HVDC system

As the TSOs do not seem to be interested and willing to take the extra risks and cost of implementing these, progress may only be achieved with a stronger involvement from the governments at national and European level.

4.2.4. Governments

The realisation of multi-terminal VSC HVDC schemes in Europe should be stimulated as soon as possible. A first attempt to do this is the Horizon2020 call LCE-05, which calls for a meshed offshore HVDC grid. However, the implementation of a meshed offshore HVDC grid seems to be very optimistic considering the background that not even a non-meshed onshore three-terminal VSC HVDC system has been realised in Europe. This led to a very limited response from the TSOs towards the call LCE-05, and it is unclear, if any and what kind of activities will result from this call.

To achieve progress, more support for multi-terminal DC technology is definitely needed. Support should focus on realistic intermediate targets like the two proposed demonstration projects, instead of calling for a full-scale meshed offshore super grid from scratch.

References

[1] G. Asplund, K. Linden, A. Marzin, C. Barker, J. Rittiger, N. Pahalawaththa, R. Iravani, D. V. Hertem, D. Jovcic, K. Soegaard, U. Baur, P. Christensen, P. Labra, M. Rashwan, J. Berteen, S. Cole, E.-D. Wilkening, D. Westermann, C. Yue, and W. Jialiang, "CIGRE WG B4.52 - Technical Brochure 533 - HVDC Grid Feasibility Study", *CIGRE*, 2013.

[2] FOSG WG 2, "Roadmap to the Supergrid Technologies - Update Report", *Friends of the Supergrid*, 2014.

[3] J. d. Decker, P. Kreutzkamp, P. Joseph, A. Woyte, S. Cowdroy, P. McGarley, L. Warland, H. Svendsen, J. Voelker, C. Funk, H. Peinl, J. Tambke, L. v. Bremen, K. Michalowska, and G. Caralis, "Offshore Electricity Grid Infrastructure in Europe", *OffshoreGrid Project*, 2011.

[4] NSCOGI WG 1 - Grid Configuration, "The North Seas Countries' Offshore Grid Initiative - Initial Findings", 2012.

[5] ENTSO-E - Regional Group North Sea, "Offshore Transmission Technology", *ENTSO-E*, 2012.

[6] S. Cole, "Steady-State And Dynamic Modelling of VSC HVDC Systems for Power System Simulation", *Dissertation Katholieke Universoteit Leuven*, 2010.

[7] N. Flourentzou, V. G. Agelidis, and G. D. Demetriades, "VSC-based HVDC power transmission systems: An overview", *IEEE Transactions on Power Electronics*, vol. 24, pp. 592-602, 2009.

[8] C. Meyer, "Key components for future offshore dc grids": Shaker, 2007.

[9] L. Max, "Design and Control of a DC Collection Grid for a Wind Farm", *Dissertation Chalmers University of Technology*, 2009.

[10] H. Nakao, M. Hirose, T. Sakai, N. Kawamura, H. Miyata, M. Kadowaki, T. Oomori, and A. Watanabe, "The 1,400-MW Kii-Channel HVDC System", *Hitachi Review*, vol. 50, 2001.

[11] T. Shimato, T. Hashimoto, and M. Sampei, "The Kii Channel HVDC Link in Japan", presented at the CIGRE, Paris, 2002.

[12] Prysmian Cables & Systems, "Extrueded Cables for HVDC Power Transmission", 2014.

[13] Western Link Project, "Western Link Project", http://www.westernhvdclink.co.uk, 2014.

[14] P. L. Francos, S. S. Verdugo, H. F. Alvarez, S. Guyomarch, and J. Loncle, "INELFE - Europe's first integrated onshore HVDC interconnection", in *IEEE PES General Meeting*, 2012, pp. 1-8.

[15] A. Gustafsson, M. Saltzer, A. Farkas, H. Ghorbani, T. Quist, and M. Jeroense, "The new 525 kV extruded HVDC cable system", ed: ABB Grid Systems, 2014.

[16] Nexans, "NordLink HVDC interconnector between Norway and Germany will use Nexans' subsea power cables".

[17] M. Barnes and A. Beddard, "Voltage Source Converter HVDC Links - The State of the Art and Issues Going Forward", *Energy Procedia*, vol. 24, pp. 108-122, 2012.

[18] G. Asplund, K. Eriksson, and K. Svensson, "DC Transmission based on Voltage Source Converters", presented at the CIGRE SC14 Colloquium, South Africa, 1997.

[19] B. D. Railing, J. J. Miller, P. Steckley, G. Moreau, P. Bard, L. Ronström, and J. Lindberg, "Cross Sound cable project–Second generation VSC technology for HVDC", in *CIGRE*, Paris, 2004.

[20] L. Ronström, M. L. Hoffstein, R. Pajo, and M. Lahtinen, "The Estlink HVDC Light Transmission System", in *CIGRE Regional Meeting*, Tallinn, Estonia, 2007.

[21] J. Glasdam, C. L. Bak, L. Kocewiak, and J. Hjerrild, "Review on Multi-Level Voltage Source Converter Based HVDC Technologies for Grid Connection of Large Offshore Wind Farms", 2012.

[22] J. Peralta, H. Saad, S. Dennetiere, J. Mahseredijan, and S. Nguefeu, "Detailed and Averaged Models for a 401-Level MMC–HVDC System", *IEEE Transaction on Power Delivery*, vol. 27, 2012.

[23] ABB - HVDC, "HVDC References", 2015.

[24] ABB, "DolWin2 - ABB's offshore connection will help reduce CO2 emissions by more than three million tons per year", 2012.

[25] B. R. Andersen, L. Xu, and K. T. G. Wong, "Topologies for VSC transmission", 2001, pp. 298-304.

[26] U. N. Gnanarathna, A. M. Gole, and R. P. Jayasinghe, "Efficient modeling of modular multilevel HVDC converters (MMC) on electromagnetic transient simulation programs", *IEEE Transactions on Power Delivery,* vol. 26, pp. 316-324, 2011.

[27] U. Wijk, J. Lindgren, J. Winther, and S. Nyberg, "DolWin 1 - Further Achievements in HVDC Offshore Connections", presented at the EWEA Offshore, Frankfurt, 2013.

[28] ABB Grid Systems - HVDC, "Skagerrak 4 - Excellent benefits through interconnections ", ed, 2014.

[29] T. Nakajima and S. Irokawa, "A Control System for HVDC Transmission by Voltage Sourced Converters", 1999.

[30] ABB news releases, "Creating Scotland’s Caithness Moray subsea HVDC power link ", 2014.

[31] ABB Grid Systems - HVDC. (2013, HVDC Light - It's time to connect.

[32] T. Halder, "Hot modeling and simulation of high voltage direct current (HVDC) power transmission", in *IEEE International Conference Power Electronics, Drives and Energy Systems (PEDES)*, 2012, pp. 1-6.

[33] C. Xia, S. Haishun, W. Jinyu, L. Wei-Jen, Y. Xufeng, L. Naihu, and Y. Liangzhong, "Integrating Wind Farm to the Grid Using Hybrid Multiterminal HVDC Technology", *IEEE Transactions on Industry Applications,* vol. 47, pp. 965-972, 2011.

[34] R. E. Torres-Olguin, M. Molinas, and T. M. Undeland, "Offshore Wind Farm Grid Integration by VSC Technology With LCC-Based HVDC Transmission", *IEEE Transactions on Sustainable Energy,* vol. 3, pp. 899-907, 2012.

[35] P. Wulue, C. Yong, and C. Hairong, "Hybrid Multi-terminal HVDC System for Large Scale Wind Power", in *Power Systems Conference and Exposition (PSCE)*, 2006, pp. 755-759.

[36] A. Garces Ruiz, "Design, Operation and Control of Series-Connected Power Converters for Offshore Wind Parks", Norwegian University of Science and Technology, 2012.

[37] C. D. Barker and R. S. Whitehouse, "A current flow controller for use in HVDC grids", in *10th IET International Conference on AC and DC Power Transmission (ACDC)*, 2012, pp. 1-5.

[38] R. L. Steigerwald, R. W. de Doncker, and H. Kheraluwala, "A comparison of high-power DC-DC soft-switched converter topologies", *IEEE Transactions on Industry Applications,* vol. 32, pp. 1139-1145, 1996.

[39] A. Hagar, "A New Family of Transformerless Modular DC-DC Converters for High Power Applications", University of Toronto, 2011.

[40] J. Taufiq, "Power electronics technologies for railway vehicles", in *Power Conversion Conference (PCC)*, Nagoya, 2007, pp. 1388-1393.

[41] D. Zuber, "Mittelfrequente resonante DC/DC-Wandler für Traktionsanwendungen", *Dissertation ETH,* 2001.

[42] L. Yang, T. Zhao, J. Wang, and A. Q. Huang, "Design and Analysis of a 270kW Five-level DC/DC Converter for Solid State Transformer Using 10kV SiC Power Devices", in *Power Electronics Specialists Conference (PESC)*, 2007, pp. 245-251.

[43] M. Steiner and H. Reinold, "Medium frequency topology in railway applications", in *European Conference on Power Electronics and Applications*, 2007, pp. 1-10.

[44] G. Ortiz, J. Biela, D. Bortis, and J. W. Kolar, "1 Megawatt, 20 kHz, isolated, bidirectional 12kV to 1.2 kV DC-DC converter for renewable energy applications", in *International Power Electronics Conference (IPEC)*, 2010, pp. 3212-3219.

[45] S. Meier, T. Kjellqvist, S. Norrga, and H. P. Nee, "Design considerations for medium-frequency power transformers in offshore wind farms", in *13th European Conference on Power Electronics and Applications (EPE)*, 2009, pp. 1-12.

[46] C. D. Barker, C. C. Davidson, D. R. Trainer, and R. S. Whitehouse, "Requirements of DC-DC Converters to facilitate large DC Grids", in *CIGRE Symposion*, 2012.

[47] F. Zhang, L. Du, F. Z. Peng, and Z. Qian, "A new design method for high-power high-efficiency switched-capacitor DC-DC converters", *IEEE Transactions on Power Electronics,* vol. 23, pp. 832-840, 2008.

[48] D. Jovcic, "Bidirectional, High-Power DC Transformer", *IEEE Transactions on Power Delivery*, vol. 24, pp. 2276-2283, 2009.

[49] F. H. Khan and L. M. Tolbert, "A Multilevel Modular Capacitor-Clamped DC-DC Converter", *IEEE Transactions on Industry Applications*, vol. 43, pp. 1628-1638, 2007.

[50] M. M. Walter and C. M. Franck, "Influence of arc chamber parameters on passive resonance circuit of HVDC circuit breakers", 2011.

[51] D. Schmitt, Y. Wang, T. Weyh, and R. Marquardt, "DC-side fault current management in extended multiterminal-HVDC-grids", in *9th International Multi-Conference on Systems Signals and Devices (SSD)*, 2012, pp. 1-5.

[52] D. Andersson and A. Henriksson, "Passive and active DC breakers in the three Gorges-Changzhou HVDC project", in *International Conference on Power Systems, Wuhan, China*, 2001.

[53] M. Callavik, "ABB achieves another milestone in electrical engineering - The hybrid HVDC breaker", ed: ABB, 2012.

[54] J. Haefner and B. Jacobson, "Proactive Hybrid HVDC Breakers - A key innovation for reliable HVDC grids", presented at the CIGRE, Bologna, 2011.

[55] F. Deng and Z. Chen, "Design of Protective Inductors for HVDC Transmission Line Within DC Grid Offshore Wind Farms", 2013.

[56] M. Y. Haj-Maharsi, "Novel DC Ring Topology and Protection System–a Comprehensive Solution for mega city power grids", 2010.

[57] University of Birmingham, "High Voltage Direct Current Power Converter", Great Britain Patent PCT/GB2012/052936, 2012.

[58] IET, "Alpha Ventus", *www.theiet.org*, 2015.

[59] 4C Offshore, "BorWin Alpha with Jacket", *www.4coffshore.com*, 2014-10-16 2014.

[60] Rigzone, "North Rankin B Platform", *www.rigzone.com*, 2015.

[61] Maritime Journal, "Concrete gravity foundations, the future for windfarms", *http://www.maritimejournal.com*, 2014-10-16 2013.

[62] Siemens, "Siemens", *www.siemens.com*, 2015.

[63] O. Saetre, *Teknisk Ukeblad*, 2014.

[64] M. Hyttinen, J.-O. Lamell, and T. F. Nestli, "New application of voltage source converter (VSC) HVDC to be installed on the gas platform Troll A ", presented at the CIGRE, Paris, 2004.

[65] Wikipedia. Available: http://de.wikipedia.org/wiki/Offshore-Windpark

[66] E. Bachynski. (2012, Design and Analysis of Floating Platforms of Floating Platforms for Wind Turbines for Wind Turbines.

[67] Power magazine, "Top Plants: Hywind Floating Wind Turbine, North Sea, Norway". Available: http://www.powermag.com

[68] T. Ishihara and S. Taki, "Fukushima Floating Offshore Wind Farm Demonstration Project - Construction of Phase I -".

[69] Perdido Spar, "Perdido Spar", *www.arabianoilandgas.com*, 2015.

[70] N. Fichaux, J. Wilkes, F. van Hulle, and A. Cronin, "Oceans of opportunity", *European Wind Energy Association, Technical Report*, 2009.

[71] S. Succar and R. H. Williams, "Compressed air energy storage: Theory, resources, and applications for wind power", *Princeton environmental institute report*, vol. 8, 2008.

[72] Green Prophet, "Arothron's Underwater Compressed Air Storage Could Fill Gaps in the Grid". Available: http://www.greenprophet.com

[73] J. I. S. Martin, I. Zamora, J. J. S. Martin, V. Aperribay, and P. Eguia, "Energy Storage Technologies for Electric Applications", presented at the International Conference on Renewable Energies and Power Quality (ICREPQ), Las Palmas de Gran Canaria, 2011.

[74] A. H. Slocum, G. E. Fennell, G. Duendar, B. G. Hodder, J. D. C. Meredith, and M. A. Sager, "Ocean Renewable Energy Storage (ORES) System: Analysis of an Undersea Energy Storage Concept", *Proceedings of the IEEE*, vol. 101, 2013.

[75] W. W. d. Boer, F. J. Verheij, D. Zwemmer, and R. Das, "The Energy Island - An Inverse Pump Accumulation Station", presented at the EWEC, Milano, 2007.

[76] CIGRE Working Group B4.58, "CIGRE Technical Brochure B4-58", ~2015.

[77] E. Prieto-Araujo, F. D. Bianchi, A. Junyent-Ferrex, and O. Gomis-Bellmunt, "Methodology for Droop Control Dynamic Analysis of Multiterminal VSC-HVDC Grids for Offshore Wind Farms", *IEEE Transactions on Power Delivery*, vol. 26, pp. 2476-2485, 2011.

[78] T. K. Vrana, J. Beerten, R. Belmans, and O. B. Fosso, "A classification of DC node voltage control methods for HVDC grids", *Electric Power System Research*, vol. 103, 2013.

[79] T. K. Vrana, L. Zeni, and O. B. Fosso, "Active Power Control with Undead-Band Voltage & Frequency Droop for HVDC Converters in Large Meshed DC Grids", presented at the EWEA Conference, Copenhagen, 2012.

[80] T. K. Vrana, L. Zeni, and O. B. Fosso, "Dynamic Active Power Control with Improved Undead-Band Droop for HVDC Grids", presented at the IET ACDC Conference, Birmingham, 2012.

[81] B. Lundqvist, "100 years of relay protection, the Swedish ABB relay history", *Sweden.[Online]*, 2010.

[82] D. van Hertem, M. Ghandhari, and M. Delimar, "Technical limitations towards a SuperGrid 2014; A European prospective", in *IEEE International Energy Conference and Exhibition (EnergyCon)*, 2010, pp. 302-309.

[83] K. de Kerf, K. Srivastava, M. Reza, D. Bekaert, S. Cole, D. van Hertem, and R. Belmans, "Wavelet-based protection strategy for DC faults in multi-terminal VSC HVDC systems", *IET Generation, Transmission & Distribution*, vol. 5, pp. 496-503, 2011.

[84] I. Farhat, "Fault detection, classification and location in trasmission line systems using neural networks ", Master of Applied Science, Concordia University 2003.

[85] D. Naidoo and N. M. Ijumba, "HVDC line protection for the proposed future HVDC systems", in *International Conference on Power System Technology (PowerCon)*, 2004, pp. 1327-1332.

[86] D. Naidoo, "Protection of ultra long HVDC transmission lines", 2011.

[87] J. Yang, J. E. Fletcher, and J. O'Reilly, "Multiterminal DC wind farm collection grid internal fault analysis and protection design", *IEEE Transactions on Power Delivery*, vol. 25, pp. 2308-2318, 2010.

[88] J. Suonan, S. Gao, G. Song, Z. Jiao, and X. Kang, "A novel fault-location method for HVDC transmission lines", *IEEE Transactions on Power Delivery*, vol. 25, pp. 1203-1209, 2010.

[89] House of Commons - Energy and Climate Change Committee, "A European Supergrid".

[90] 4C Offshore, "Offshore HVDC Converter & HVDC Grid Collector Database", http://www.4coffshore.com/windfarms/converters.aspx, 2014-10-23 2014.

[91] S. Knight, "Bard 1 transmission problems continue", *Wind Power Offshore*, 2014.

[92] U. Leuschner, "Netzanbindung akzeptiert 'schmutzigen' Strom von Offshore-Windpark nicht", *Energie-Chronik*, 2014.

[93] U. Leuschner, "Vierter Offshore-Windpark in der Nordsee am Netz", *Energie-Chronik*, 2014.

[94] C. Gerlach, "Kein Strom: Letzte Chance für BARD Offshore 1", *NRD.de*, 2014.

A Collected Data on VSC HVDC converters

This table contain data about real VSC HVDC converter projects until 2020, which are existing, under construction or at least confirmed. These data have been collected from a variety of sources, and accuracy cannot be guaranteed. Exceptional data are highlighted in red font.

Project	Country	Year	Manu-facturer	HVDC-Link Power [MW]	Number of Parallel Systems	HVDC-Syst. Power [MW]	HVDC-Syst. Voltage [kV]	Polarity	Number of Series Converters	Configuration	Converter DC Voltage [kV]	Converter DC Power [MW]	Converter DC Current [kA]	Number of Offshore	Converter 1 AC Voltage [kV]	Converter 2 AC Voltage [kV]	HVDC Generation	Number of Converter Levels	Number of System Terminals	Special Information
Haellsjoen	Sweden	1997	ABB	3	1	3	10	Both	1	Sym. Monop.	20	3	0.15	0	10	10	0	2	2	
Gotland	Sweden	1999	ABB	50	1	50	80	Both	1	Sym. Monop.	160	50	0.31	0	77	77	1	2	2	
Shin-Shinano	Japan	1999	Several Japanese	38	1	38	11		1	Asym. Monop.	11	38	3.45	0	66	275	0		3	Back-to-back
Terranora 1+2+3 (DirectLink)	Australia	2000	ABB	180	3	60	80	Both	1	Sym. Monop.	160	60	0.38	0	110	132	1	2	2	
Tjaereborg	Danmark	2000	ABB	7	1	7	9	Both	1	Sym. Monop.	18	7	0.39	0	11	11	0	2	2	
Eagle Pass	USA	2000	ABB	36	1	36	16	Both	1	Sym. Monop.	32	36	1.13	0	138	138	2	3	2	Back-to-back
Cross sound	USA	2002	ABB	330	1	330	150	Both	1	Sym. Monop.	300	330	1.10	0	138	345	2	3	2	
Murraylink	Australia	2002	ABB	220	1	220	150	Both	1	Sym. Monop.	300	220	0.73	0	132	220	2	3	2	
Troll A 1+2	Norway	2005	ABB	88	2	44	60	Both	1	Sym. Monop.	120	44	0.37	1	56	132			2	
Estlink 1	Finland - Estonia	2006	ABB	350	1	350	150	Both	1	Sym. Monop.	300	350	1.17	0	330	400	3	2	2	
BorWin 1	Germany	2009	ABB	400	1	400	150	Both	1	Sym. Monop.	300	400	1.33	1	170	400	3	2	2	
Caprivi	Namibia	2010	ABB	300	1	300	350	Neg.	1	Asym. Monop.	350	300	0.86	0	330	400	3	2	2	Incomplete bipole
Trans Bay Cable	USA	2010	Siemens	400	1	400	200	Both	1	Sym. Monop.	400	400	1.00	0	138	230	4a	217?	2	first MMC
Valhall	Norway	2011	ABB	78	1	78	150	Neg.	1	Asym. Monop.	150	78	0.52	1	11	300	3	2	2	
Nanhui	China	2011	C-EPRI	18	1	18	30	Both	1	Sym. Monop.	60	18	0.30	0	35	35	0		2	
East-West Interconnector	UK - Ireland	2013	ABB	500	1	500	200	Both	1	Sym. Monop.	400	500	1.25	0	400	400	3	2	2	
Guangdong-	China	2014	Rongxin /	200	1	200	160	Both	1	Sym.	320	200	0.63	0	110	110	4a		3	Power ratings 200 -

Nanao			NR / XiDian							Monop.										100 - 50
Zhoushan	China	2014	C-EPRI / NR	400	1	400	200	Both	1	Sym. Monop.	400	400	1.00	0	110	220	4a		5	Power ratings 400 - 300 - 100 - 100 - 100
Mackinac	USA	2014	ABB	200	1	200	71	Both	1	Sym. Monop.	142	200	1.41	0	138	138	4b	9	2	
HelWin 1	Germany	2014	Siemens	576	1	576	250	Both	1	Sym. Monop.	500	576	1.15	1	155	250	4a		2	
Skagerrak 4	Norway - Danmark	2015	ABB	700	1	700	500	Var.	1+1	Asym. Monop.	500	700	1.40	0	400	400	4b	29	2	Part of hybrid bipole, other half is CSC
NordBalt	Lithuania - Sweden	2015	ABB	700	1	700	300	Both	1	Sym. Monop.	600	700	1.17	0	330	400			2	
INELFE 1+2	Spain - France	2015	Siemens	2000	2	1000	320	Both	1	Sym. Monop.	640	1000	1.56	0	400	400	4a	401	2	Most powerful
Troll A 3+4	Norway	2015	ABB	100	2	50	60	Both	1	Sym. Monop.	120	50	0.42	1	66	132	3	2	2	
Tres Amigas	USA	2015	Alstom	750	1	750	326	Both	1	Sym. Monop.	652	750	1.15	0	345	345	4a		2	Back-to-back
South-(West) Link 1+2	Sweden	2015	Alstom	1440	2	720	300	Both	1	Sym. Monop.	600	720	1.20	0	400	400	4a		2	
DolWin 1	Germany	2015	ABB	800	1	800	320	Both	1	Sym. Monop.	640	800	1.25	1	155	400	3	2	2	
BorWin 2	Germany	2015	Siemens	800	1	800	300	Both	1	Sym. Monop.	600	800	1.33	1	155	400	4a		2	
SylWin 1	Germany	2015	Siemens	864	1	864	320	Both	1	Sym. Monop.	640	864	1.35	1	155	400	4a		2	
HelWin 2	Germany	2015	Siemens	690	1	690	320	Both	1	Sym. Monop.	640	690	1.08	1	155	400	4a		2	
Aaland	Finland	2015	ABB	100	1	100	80	Both	1	Sym. Monop.	160	100	0,63	0	110	110	3	2	2	
DolWin 2	Germany	2016	ABB	900	1	900	320	Both	1	Sym. Monop.	640	900	1.41	1	155	400	4b	37	2	
Maritime Link	Canada	2017	ABB	500	1	500	200	Both	2	Bipole	200	250	1.25	0	230	345	4b	11	2	First VSC bipole
Dalian City	China	2017	C-EPRI	1000	1	1000	320	Both	1	Sym. Monop.	640	1000	1.56	0			4a		2	
DolWin 3	Germany	2018	Alstom	900	1	900	320	Both	1	Sym. Monop.	640	900	1.41	1			4a		2	
Caithness Moray (Shetland)	UK - Ireland	2018	ABB	1200	1	1200	320	Both	1	Sym. Monop.	640	1200	1.88	0			4b	37	2+1?	Power ratings 1200 - 800, third terminal?
BorWin 3	Germany	2019	Siemens	900	1	900	320	Both	1	Sym. Monop.	640	900	1.41	1			4a		2	
Johan Sverdrup	Norway	2019	ABB	100	1	100	50	Both	1	Sym. Monop.	160	100	0.63	1	33	300	3	2	2	
NordLink	Norway - Germany	2020	ABB	1400	1	1400	525	Both	2?	Bipole?	525	700	1.33	0	400	400	4b	29	2	

B Collected Data on XLPE HVDC Cables

This table contain data about real XLPE HVDC cable projects until 2020, which are existing, under construction or at least confirmed. These data have been collected from a variety of sources, and accuracy cannot be guaranteed. Exceptional data are highlighted in red font.

Project	Country	Year	Manufacturer	DC Voltage [kV]	Power [MW]	DC Current [kA]	Length [km]	Number of Parallel Circuits	Number
Gotland	Sweden	1999	ABB	80	25	0.31	70		2
Terranora 1+2+3 (DirectLink)	Australia	2000	ABB	80	30	0.38	59	3	3*2
Murraylink	Australia	2002	ABB	150	110	0.73	180		2
Cross Sound	USA	2002	ABB	150	165	1.10	40		2
Troll A 1+2	Norway	2002	ABB	60	22	0.37	70	2	2*2
Estlink 1	Finland - Estonia	2006	ABB	150	175	1.17	105		2
BorWin 1	Germany	2009	ABB	150	200	1.33	200		2
Trans Bay	USA	2010	Prysmian	200	200	1.00	85		2
East-West Inter-connector	UK - Ireland	2013	ABB	200	250	1.25	261		2
Guangdong-Nanao	China	2014	ZTT + other Chinese	160	100	0.63	32		2
HelWin 1	Germany	2014	Prysmian	250	288	1.15	130		2
Troll A 3+4	Norway	2015	ABB	60	25	0.42	70	2	2*2
NordBalt	Sweden - Lithuania	2015	ABB	300	350	1.17	450		2
DolWin 1	Germany	2015	ABB	320	400	1.25	165		2
BorWin 2	Germany	2015	Prysmian	300	400	1.33	200		2
HelWin 2	Germany	2015	Prysmian	320	345	1.08	131		2
SylWin 1	Germany	2015	Prysmian	320	432	1.35	210		2
INELFE	France - Spain	2015	Prysmian	320	500	1.56	60	2	2*2
South-(West) Link	Sweden	2015	ABB	300	360	1.20	192	2	2*2
DolWin 2	Germany	2016	ABB	320	450	1.41	135		2
DolWin 3	Germany	2018	Prysmian	320	450	1.41	162		2
BorWin 3	Germany	2019	Prysmian	320	450	1.41	160		2
Caithness Moray (Shetland)	UK	2018	ABB	320	600	1.88	160		2
Johan Sverdrup	Norway	2019	ABB	80	50	0.63	200		2

C Collected Data on MI HVDC Cables

This table contain data about real MI HVDC cable projects until 2020, which are existing, under construction or at least confirmed. These data have been collected from a variety of sources, and accuracy cannot be guaranteed. Exceptional data are highlighted in red font.

Project	Country	Year	Manufacturer	Number	DC Voltage [kV]	Power [MW]	DC Current [kA]	Length [km]	Special Information
Konti-Skan 1	Sweden - Danmark	1965	ABB	1	250	250	1.00	87	
Skagerrak 1	Norway - Danmark	1976	ABB	1	250	250	1.00	127	
Skagerrak 2	Norway - Danmark	1977	ABB	1	250	250	1.00	127	
Gotland 2	Sweden	1983	ABB	1	150	130	0.87	96	
Gotland 3	Sweden	1987	ABB	1	150	130	0.87	96	
Konti-Skan 2	Sweden - Danmark	1988	ABB	1	300	300	1.00	88	
Fenno-Skan 1	Sweden - Finland	1989	ABB	1	400	500	1.25	200	
Skagerrak 3	Norway - Danmark	1993	ABB	1	350	500	1.43	127	
Baltic Cable	Sweden - Germany	1994	ABB	1	450	600	1.33	250	
Kontek	Danmark - Germany	1995	ABB	1	400	600	1.50	171	
SwePol	Sweden - Poland	2000	ABB	1	450	600	1.33	254	
Neptune	USA	2007	Prysmian	1	500	660	1.32	105	
NorNed	Norway - Nederland	2008	ABB, Nexans	2	450	350	0.78	580	2-Core Cable
Storebælt	Danmark	2010	ABB	1	400	600	1.50	58	
Fenno-Skan 2	Sweden - Finland	2011	Nexans	1	500	800	1.60	200	
BritNed	Nederland - UK	2011	ABB	2	450	500	1.11	260	
SAPEI	Italy	2011	Prysmian	2	500	500	1.00	420	
EstLink 2	Finland - Estonia	2014	Nexans	1	450	650	1.44	171	
Skagerrak 4	Norway - Danmark	2015	Nexans	1	500	700	1.40	240	
Western HVDC Link	UK	2016	Prysmian	2	600	1100	1.83	385	
NordLink	Norway - Germany	2020	Nexans, ABB	2	525	700	1.33	570	

D Draft Article: 'Definition and Classification of Terms for HVDC Networks'

Abstract: A systematic terminology for the field of HVDC networks has been developed, closing the gap between the well-established terminologies from AC power systems and HVDC technology. The most relevant items, topologies and concepts have been given clear and unique defined names, and these have been classified in a systematic way. The motivation for this work was to help avoiding observed communication problems which are emerging when power system engineers talk to HVDC technology engineers. The main guideline of the approach was to minimise conflicts with the mentioned two existing terminologies and with existing publications on HVDC networks. A significant effort has been made to design the terminology "future-proof" not only covering today's HVDC technology but also potential future developments like large meshed HVDC grids and high power HVDC-HVDC converters.

This article has been submitted to the CIGRE Science&Engineering Journal in May 2015. The full text is attached here.

Definition and Classification of Terms for HVDC Networks

Til Kristian Vrana, Sintef Energi
Keith Bell, University of Strathclyde
Poul Ejnar Sørensen, DTU Wind Energy
Tobias Hennig, Fraunhofer IWES

Keywords: Power System, HVDC Network, HVDC Grid, HVDC System, Multi-Terminal HVDC, MTDC, Super Grid, HVDC Hub, Supernode, Meshed HVDC, Radial HVDC.

1 Introduction

The scientific community has gained a strong interest in the field of High Voltage Direct Current (HVDC) networks. In most publications these are referred to as HVDC grids or HVDC systems. The entire field of research is at the moment lacking a systematic terminology, as there are two existing fields merging: Electrical power systems (AC) and HVDC technology. This can result in communication problems, as many terms in use do not have a clear and unique definition.

The North Sea Offshore and Storage Network (NSON) Initiative has identified this lack of a terminology and definition of terms as problematic for the development of the electrical infrastructure in the North Sea region, and therefore worked to develop the missing terminology, which is presented in this article.

1.1 Simplifications

In this article, a single-line-representation of all HVDC infrastructure is used. This is necessary to enable for a systematic view upon the network topology, without having to go into technical detail.

What is referred to here as one DC bus is in technical detail either two busses (e.g. positive and negative poles) or three busses (additional ground), and one DC transmission line can be all from one conductor (with ground/sea return) to three conductors (for plus, minus and metallic return). A HVDC system is referred to as one single voltage level, even though an asymmetric monopole has a different voltage at the return (e.g. -150 kV / 0 kV). These details are however not in focus in this article.

All converters are regarded as ideal converters. Only the input and output are considered, and all technical details of the internal topology including intermediate voltage levels are disregarded.

Very short transmission lines are ignored. Two busses that are co-located and directly connected (by a very short transmission line) are combined into one equivalent bus (e.g. the conductors connecting converter terminals of a back-to-back system).

1.2 Visualisations

The concepts are visualised with figures using the symbols explained in Figure 1.

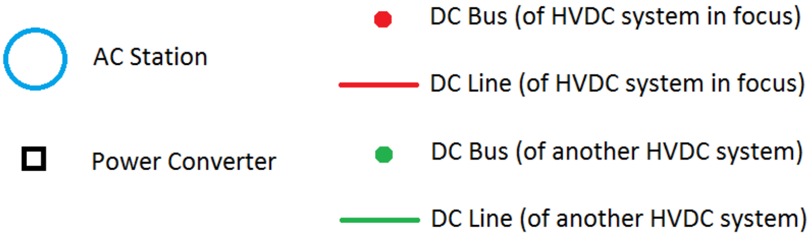

Figure 1: Symbols

The CIGRE B4 DC Test Grid [1] drawn with this simplified visualisation scheme is shown in Figure 2. This can be compared with the regular electrical drawing of the same grid, shown in Figure 24 in Section 4.

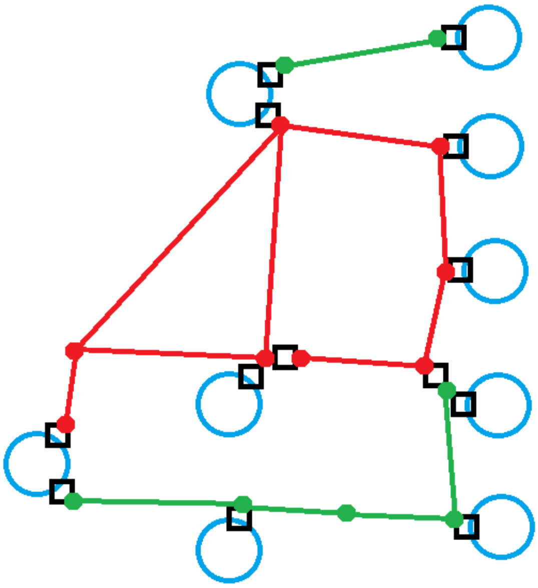

Figure 2: The CIGRE B4 DC Test Grid

2 Definitions for HVDC Networks

The relevant definitions for HVDC networks are given in this section.

2.1 HVDC Networks

A *HVDC network* is an electrical network that utilises high DC voltage. It does not need to be purely based on DC, as it can also include conversion through intermediate AC stages (DC-AC-DC conversion), but it cannot include AC transmission lines. A network consisting of AC and DC transmission lines (the interconnected European electric power grid) is a hybrid AC+DC network. Hybrid AC+DC networks are not in focus here.

In this definition a distinction is made between two types of HVDC networks: HVDC systems and HVDC grids.

2.1.1 HVDC System

A *HVDC system* is an autonomous *HVDC network*, which operates with a single high DC voltage. In a *HVDC system*, all *busses* (defined in Section 2.3) are directly connected by conductors. Protection devices like circuit breakers can be series connected within a *HVDC system*, even though that is not really a direct conductor connection. An example of a *HVDC system* is shown in Figure 3.

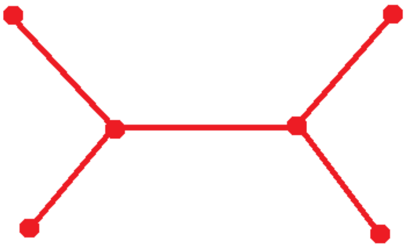

Figure 3: HVDC system

DC-DC power converters can only be series connected within a *HVDC system*, if the converter connects to two busses, which are both part of the same *HVDC system*. This is the case if they are directly connected by conductors, meaning there is a direct connection path between the busses in parallel to the DC-DC converter, creating a loop within the HVDC system (controllable mesh, Section 2.4.2). Without that parallel direct connection path, the DC-DC converter would split the *HVDC system* into two *HVDC systems* connected by the converter.

A *HVDC system* can only have one voltage level, due to the direct conductor connection. This is similar to a synchronous AC power system, which can only have one frequency.

If a short-circuit appears within a *HVDC system*, the voltage collapses in the entire *HVDC system*, if this is not prevented by a protection system, which quickly separates the faulty part form the healthy part. This is why large *HVDC systems* would have demanding requirements towards the protection system. This short-circuit behaviour is one of the most relevant differences between *HVDC systems* and HVDC grids.

A *HVDC system* can stand alone, or it can be part of a HVDC grid. In that case, it could also be referred to as a *HVDC sub-system*, to highlight the fact that it is not standing alone.

2.1.2 HVDC Grid

A *HVDC grid* is an interconnected *HVDC network*, consisting of two or more *HVDC systems, which can be referred to as sub-systems in that case*. Unlike a *HVDC system*, a *HVDC grid* does not require direct conductor connection of all *busses*. A *HVDC grid* can therefore (but does not need to) have multiple voltage levels, connected by power converters. A similarity to AC can be observed when regarding interconnected AC grids, consisting of several synchronous (sub-) systems which can (but do not need to) have multiple frequencies. In the European AC grid, all (sub-) systems have the same frequency (50 Hz), but in the Japanese AC grid, the two (sub-) systems have different frequencies (50 Hz and 60 Hz). An example of a *HVDC grid* (consisting of two *HVDC systems*) is shown in Figure 4.

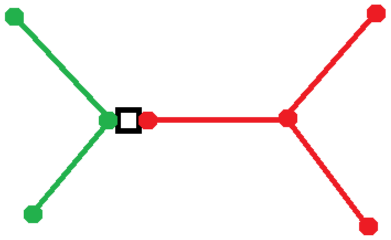

Figure 4: HVDC grid

Different *HVDC systems* can be counted as belonging to the same *HVDC grid* if:

- They are connected by a DC-DC converter
- They connect to the same AC station via AC-DC converters (see *supernode*, Section 2.3.5)

As stated, the *HVDC grid* can also include conversion through intermediate AC stages (DC-AC-DC conversion), but it cannot include AC transmission lines.

If a short-circuit appears within a *HVDC grid*, the voltage does not collapse in the entire *HVDC grid*, but only in the affected *HVDC (sub-) system*. This is why large *HVDC grids* do not necessarily have as demanding requirements towards the protection system as large *HVDC systems* do, since the sectioning of a *HVDC grid* into several smaller *HVDC (sub-) systems* can avoid a short-circuit from critically disturbing the entire *HVDC grid*. This advantage of a *HVDC grid* is requiring sufficient fault-blocking capabilities of all converter interfaces between the *HVDC (sub-) systems*.

The word 'grid' somehow implies the presence of *loops* (defined in Section 2.4). However, a large *HVDC network* consisting of several *HVDC systems* with several voltage levels, but without any *loops*, could theoretically be realised in the future. Such a non-*looped HVDC network* should theoretically not be called a grid, as it lacks the characteristic *loops* of a grid. However, AC distribution systems are often also called 'distribution grids', even though many distribution systems do not have *loops*. It seems that the word 'grid' has already been used for non-*looped* networks for many years, so the use of the word 'grid' for networks without *loops* has to be accepted.

In several publications, large *HVDC systems* are called *HVDC grids*, even though they do not consist of at least two *HVDC (sub-) systems*. This is done without stating clearly what the difference is exactly between a large *HVDC system* and a *HVDC grid*. However, it can generally be observed, that the term *HVDC system* [2] is mostly used for smaller well-defined *HVDC networks*, while *HVDC grid* [3] is referring to future larger *HVDC networks* like the envisioned European Super Grid.

2.2 Edges

An *edge* generally is a connection between two vertices, as known from graph theory. Regarding *HVDC networks*, an *edge* is defined as a connection between two *busses* of that network or the connection of one bus of that network with the external world.

This connection to the external world could be to an AC system, to a source (generation) or to a sink (load). For a *HVDC system* (not for a *HVDC grid*), it could also be the connection to another *HVDC system* by a DC-DC converter.

Parallel *edges* that connect to the same *busses* on both ends (e.g. double circuit lines, parallel converters) are seen as one *edge* of the network (observable when comparing Figure 2 with Figure 24). This is relevant in the context of connection points (defined in Section 2.3.1).

2.2.1 Branch

A *branch* of a *HVDC network* is an *edge* that connects two *busses* of that network. *Branches* should have some 'significant' length or should connect locations which are electrically separate. If two *busses* are directly connected by a conductor with 'insignificant' length, they appear as one bus from a network point-of-view.

Branches are generally either HVDC lines or DC-DC converters. A HVDC transmission line always connects two *busses* of a *HVDC network*, so it is a *branch* of that network. A DC-DC converter connecting two *busses*, which belong to the same *HVDC system*, is also a *branch* of any type of *HVDC network*. A DC-DC converter connecting two *busses*, which do not belong to the same *HVDC system*, is a more complicated case, treated in Section 2.2.3.

Examples of *branches* are shown in Figure 5.

Figure 5: *Branches*

2.2.2 Terminal

A *terminal* of a *HVDC network* is an *edge* that connects one bus of that network with the external world (anything that is not part of the *HVDC network*). *Terminals* act as source and sink, or in other words as input and output.

In most cases, a *terminal* is a connection of a *HVDC network* to a power converter. However, other non-converter-type *terminals* are theoretically possible (e.g. DC load, DC generator), but those are not common, especially at high DC voltage.

All AC-DC converters are *terminals* to any type of *HVDC networks* (shown in Figure 6). A DC-DC converter connecting two *busses*, which do not belong to the same *HVDC system*, is a more complicated case, treated in Section 2.2.3.

When considering the entire complete hybrid AC+DC grid, only generation and load would remain as *terminals*, while all converters become *branches*. However, the focus here is on *HVDC networks* and not on hybrid AC+DC networks.

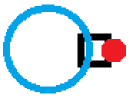

Figure 6: *Terminal*

Terminals are the points of the network where most of the inflow and outflow (current/power) is located.

Concerning current, this flow-based definition holds very well for *HVDC systems*. Only small amounts of current enter and leave the *HVDC system* at *branches*. This is the leakage currents at transmission lines and difference between input and output current of a DC-DC converter (which is small for a DC-DC converter with the same voltage level on both sides). For *HVDC grids* with different voltage levels, this flow-based definition only holds when using per unit values. This is because of the significant difference between input and output current of a DC-DC converter connecting two different voltage levels (which disappears when converting to per unit).

Concerning power, this flow-based definition is not as exact as for currents. This is due to the transmission losses on the lines (mostly power losses, very little current losses). However, when considering power, *HVDC grids* with different voltage levels can be considered without having to look at per unit values.

It is important to distinguish between *busses* and *terminals*. These two terms are often confused, as the majority of existing *HVDC systems* has one *terminal* per bus. Based on the definition of a *terminal* as given here, a *terminal* is treated as an *edge* because of the net flow through it, whereas a bus has net flow of zero.

2.2.3 HVDC System Terminal / HVDC Grid Branch Duality

A special case that needs extra attention is a DC-DC converter, which connects to two different *HVDC systems* (shown in Figure 7). This would typically be the case, when two different voltage levels are connected.

Figure 7: *HVDC system terminal - HVDC grid branch*

Regarding the *HVDC grid* (which includes both *HVDC systems*), the DC-DC converter appears as a *branch* of the grid (just like any other DC-DC converter). Regarding the two *HVDC systems*, the DC-DC converter appears as a *terminal* for both systems (unlike other DC-DC converters than can appear as a *branch* within one *HVDC system*).

2.3 Busses

A *bus* is a point in the *HVDC network* where two or more *edges* are connected. The different types of *busses* are defined here. In graph theory the term 'vertex' is used for what here is called a *bus*.

2.3.1 Connection Point

A *connection point* is defined as a *bus* where exactly two *edges* are connected together (shown in Figure 8). This is typically a connection of a converter to a transmission line or an overhead line to a cable. Since a double circuit line counts as one *edge* and not as two, a *bus* where a converter is connected to a double circuit line is considered a *connection point.*

Figure 8: ***Connection points***

Theoretically any point on any line (e.g. a cable joint) could be seen as a *connection point* of two line segments. It highly depends on the on the specific study case, if such *connection points* are relevant to be considered or not.

Connection points are not significant for power flow calculations, as the flow out of the first *edge* is exactly the flow into the other *edge*. There is no degree of freedom, so *connection points* (unlike the other *bus* types) do not add to complexity of a power flow calculation.

2.3.2 Node

A *node* is a *bus* where at least three *edges* meet, and at least one of the *edges* has to be a *terminal*.

A *bus* appears as a *node* in both types of *HVDC networks* if it has an *edge*, which connects to something outside the *HVDC grid*, and not just to another voltage level (which is part of the *HVDC grid* but not of the *HVDC system*). This usually means a connection to AC.

Examples of *busses*, which are *nodes* for both types of *HVDC networks*, are shown in Figure 9.

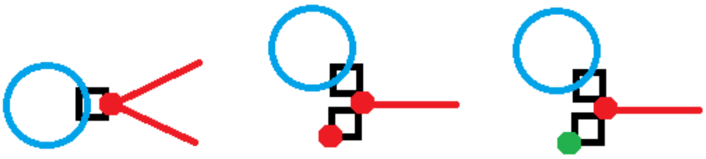

Figure 9: ***Nodes***

2.3.3 Hub

A *hub* is a *bus* where at least three *branches* meet, and where no *terminals* are connected. A *hub* here refers to a DC *hub* as a constituent part of a *HVDC network*, and not to any kind of AC *bus*. There are similarities with the term 'tee point' as used for AC networks.

A *bus* appears as a *hub* in both types of *HVDC networks* if it does not have an *edge*, which connects to something outside the *HVDC system*, not even to another voltage level (which is part of the *HVDC grid* but not of the *HVDC system*). DC-DC converters can be connected to a *hub*, if they are internal to the *HVDC system*, meaning that they connect to the same *HVDC system* on both ends. They are therefore *branches* of that *HVDC system* and not *terminals*.

Examples of *busses*, which appear as *hubs* for both types of *HVDC networks*, are shown in Figure 10. The DC-DC converters shown in the examples are internal to the *HVDC system*.

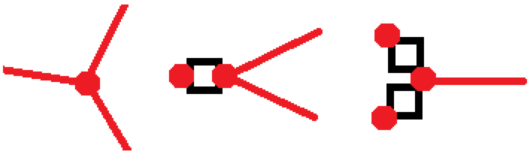

Figure 10: ***Hubs***

2.3.4 HVDC System Node / HVDC Grid Hub Duality

The definitions of *nodes* and *hubs* are identical for *HVDC grids* and *HVDC systems*, but the definition of *edges* (*branches* or *terminals*) are not identical. This duality of *branches* and *terminals* in case of DC-DC converters (explained in Section 2.2.3) results also in a duality of *nodes* and *hubs*. A *bus* with an *edge*, which is a dual *terminal*/*branch edge*, can be (but does not need to be) a dual *node*/*hub bus*.

A *bus*...

- where at least three *edges* meet
- where at least one of the *edges* is a dual *branch*/*terminal edge*

  (DC-DC converter connecting to another *HVDC system*)
- that has no connection to something outside the *HVDC grid*

...appears as a *node* for the *HVDC system*, but at the same time appears as a *hub* for the *HVDC grid*.

This is due to the fact, that the DC-DC converter appears as a *terminal* to the *HVDC system* but as a *branch* to the *HVDC grid*. Examples are shown in Figure 11.

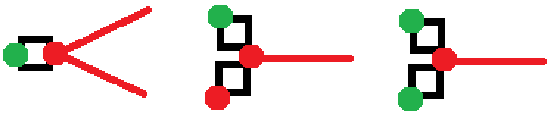

Figure 11: ***HVDC system nodes – HVDC grid hubs***

However, it should be noted:

- All *busses* that are *nodes* of a *HVDC grid* also appear as *nodes* of the corresponding *HVDC system*, but not vice versa.
- All *busses* that are *hubs* of a *HVDC system* also appear as *hubs* of the corresponding *HVDC grid*, but not vice versa.

2.3.5 Supernode

A *supernode* is not really a *bus*, but rather a cluster of *busses*. It consists of at least two (DC) *busses* and one AC station, where the *busses* are connected to the same AC station through AC-DC converters. *Supernodes* are especially relevant in the context of *pseudo-meshes* (defined in Section 2.4.3).

Examples of *supernodes* can be seen in Figure 12. The left example shows a *supernode* connecting two *busses* of the same *HVDC system*, while the right example shows a *supernode* connecting to different *HVDC systems*. All converters shown are *terminals*, as they are AC-DC converters.

Figure 12: ***Supernodes***

If the two DC *busses* of a *supernode* have the same voltage level, a switch could be placed between them, being able to short-circuit them together. This would turn the *supernode* into a regular *node* (with two parallel AC-DC converters). It enables the flexible reconfiguration between *node* and *supernode* state, depending on what is better for the specific power flow situation.

A connection to two distant AC stations in the same AC system does not qualify for a *supernode*, as it would include significant geographical transmission distance on the AC side into the *supernode*, which is in conflict with the 0-dimensional "point" character of a *bus*. For this definition, geographical distance is used instead of electrical distance. Within an AC station, there is almost no geographical distance, but the electrical distance usually is significant, due to the transformer series inductance.

A *supernode* can be seen as part of a *HVDC network*, even though it might contain an intermediate AC stage. The *supernode* (one AC station *bus* and two AC-DC converter *edges*) has some similar properties as an *edge* (DC-DC converter). It connects two DC *busses* and controls the flow between them. However, it does not fully behave like an *edge*, as the inflow on one side does not need to be equal (or almost equal) to the outflow of the other side.

Many dedicated DC-DC converter topologies also contain an intermediate AC stage (which is normally not operated at 50Hz). This does however not qualify as *supernode*, as the AC *bus* is only an AC '*connection point*' between the two converter stages, without AC '*node*' characteristics. The DC-DC converter with intermediate AC stage therefore truly behaves like an *edge*, while the *supernode* only shares some properties with an *edge*.

2.4 Loops

A *loop* is a circular structure of *branches* within a *HVDC network*. A *loop* is referred to as a cycle in graph theory. The different types of *loops* are defined here.

2.4.1 Mesh

A *mesh* is a *loop* within a *HVDC system*, where no power electronic converters are inserted in series into the *loop*, so all flows follow Ohm's and Kirchhoff's laws. The power flow in a *mesh* cannot be fully controlled. A *mesh* is shown in Figure 13.

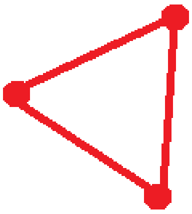

Figure 13: ***Mesh***

2.4.2 Controllable *Mesh*

A *controllable mesh* is a *loop* within a *HVDC network*, where flows can be controlled by at least one DC-DC converter inserted in series into the *loop* as a *branch*. Examples for *controllable meshes* are shown in Figure 14.

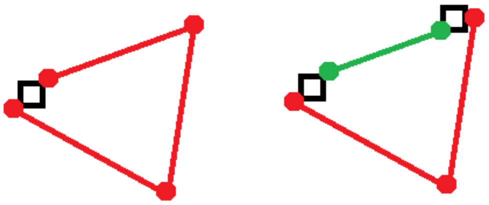

Figure 14: ***Controllable meshes***

The definition of a *controllable mesh* is identical for *HVDC grids* and *HVDC systems*. However, a *controllable mesh* of a *HVDC grid* can consist of different HVDC lines at different voltage levels belonging to different *HVDC systems*, which all are part of the same *HVDC grid* (as shown on the right of Figure 14). This is a realistic scenario for future *HVDC grids* that will consist of several voltage levels.

2.4.3 Pseudo-*Mesh*

A *pseudo-mesh* is a *loop* within the *HVDC network*, which contains at least one *supernode* (Section 2.3.5). This means that not the entire *loop* is DC, but it is closed though a DC-AC-DC connection with two AC-DC converters and one AC station. Examples of *pseudo-meshes* are shown in Figure 15.

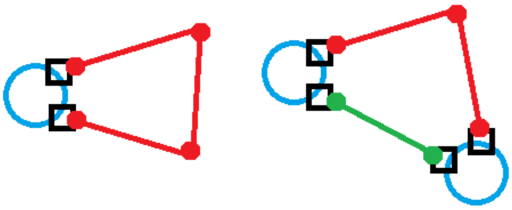

Figure 15: ***Pseudo-meshes***

The definition of a *pseudo-mesh* is identical for *HVDC grids* and *HVDC systems*. However, a *pseudo-mesh* of a *HVDC grid* can consist of different HVDC lines at different voltage levels belonging to different *HVDC systems*, which all are part of the same *HVDC grid* (as shown on the right of Figure 15). This is a likely scenario for future *HVDC grids* that will consist of several voltage levels.

If the *loop* would consist of AC and DC transmission lines, it is not regarded as a DC *pseudo-mesh*. It would be a hybrid AC+DC *loop* [4], but these are not considered here, as they do not belong to *HVDC networks* but to hybrid AC+DC networks.

3 Properties of *HVDC Systems*

The main attributes of a *HVDC system* are its complexity (in the sense of the number of inputs and outputs), its topology and its size. These three important aspects are classified here.

3.1 *HVDC System* Complexity

The input-output complexity of a *HVDC system* depends on the number of *terminals*. It is generally distinguished between two-*terminal* systems and multi-*terminal* systems.

3.1.1 Two-Terminal HVDC System

A two-*terminal* system is a *HVDC system* with two *terminals*. Only the number of *terminals* is specified, and it does not say anything about the number of *busses* and *branches*. However, systems with two *busses* and one transmission line are most common (Section 3.2.2). Some possible two-*terminal* systems are shown in Figure 16.

Figure 16: Two-*terminal HVDC systems*

The term two-*terminal* system also includes back-to-back converters with a single DC *bus* and no transmission line (e.g. first stage of Tres Amigas [5]). However, such a system can also be considered as AC-AC converter.

A two-*terminal* system can also have three or more *busses*. This would typically appear, when both cables and overhead lines are applied.

The term "point-to-point *HVDC system*" is often used synonymously for two-*terminal* system. This is however not correct, since a two-*terminal* back-to-back system is not a point-to-point system. A point-to-point system requires 'significant' geographical distance between the points. For this definition, geographical distance is used instead of electrical distance. Within a back-to-back system, there is almost no geographical distance, but the electrical distance can be significant, if there is a DC series inductor.

3.1.2 Multi-Terminal HVDC System

A multi-*terminal* system is a *HVDC system* with at least three *terminals*. Only the number of *terminals* is specified, and it does not say anything about the number of *busses* and *branches*. Any number of *terminals* (including zero) can be located at a *bus*. Some examples of multi-*terminal* systems are shown in Figure 17.

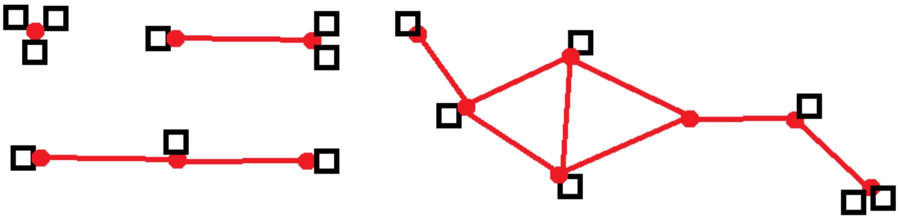

Figure 17: Multi-*terminal HVDC systems*

The term multi-*terminal* system also includes multi-*terminal* back-to-back converters with a single DC *bus* and no transmission line (e.g. Shin-Shinano [6], described in Section 3.2.1).

A multi-*terminal* system can be a point-to-point system if at least one of the two *busses* with *terminals* has more than one *terminal* (e.g. one AC-DC converter and one DC-DC converter). Two *terminals* of a *HVDC system* are considered to be at the same *bus*, if they are geographically co-located, as explained in Section 1.1.

3.2 *HVDC System* Topologies

The different *HVDC system* topologies are defined here.

3.2.1 Back-to-back *HVDC System*

A back-to-back *HVDC system* is a *HVDC system* with a single *bus* and no *branches* (examples shown in Figure 18).

Figure 18: Back-to-back *HVDC systems*

It usually has two *terminals* (left part of Figure 18), but also a system with three *terminals* has been realised (right part of Figure 18, e.g. Shin-Shinano [6]). More than three *terminals* are theoretically also possible, but this has never been applied yet, and it seems challenging to imagine an application where such a system would be the appropriate technical solution.

3.2.2 Point-to-Point *HVDC System*

A point-to-point *HVDC system* is a system where all *terminals* are located at exactly two *busses*. This implies a minimum requirement of at least two *busses*. Examples of point-to-point systems are shown in Figure 19. A point-to-point system can also have three or more *busses*. This would typically appear, when both cables and overhead lines are applied, leading to additional connection points (seen in the lower two examples of Figure 19).

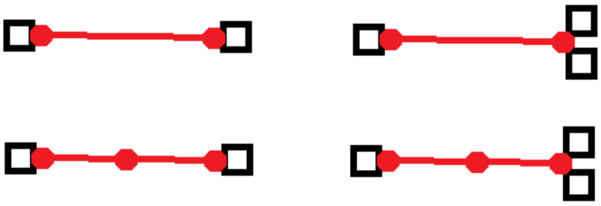

Figure 19: Point-to-point *HVDC systems*

The term "point-to-point" *HVDC system* is often used synonymously for "two-*terminal*" *HVDC system*. This is however not correct:

- Not every two-*terminal* system is a point-to-point system. If both *terminals* are located at the same *bus* (back-to-back system), the two-*terminal* system is not a point-to-point system.
- Not every point-to-point system is a two-*terminal* system. A point-to-point system can be a multi-*terminal* system if at least one of the two *busses* with *terminals* has more than one *terminal* (e.g. one AC-DC converter and one DC-DC converter). This is shown in in Figure 19 (the two point-to-point systems on the right are multi-*terminal* systems).

The term "point-to-point" system therefore contains no information about the number of *terminals*, but it rather relates to the *HVDC system* topology. This confusion originates from the fact, that most of the existing *HVDC systems* are point-to-point two-*terminal HVDC systems*.

3.2.3 Radial HVDC system

A radial *HVDC system* is a multi-*terminal HVDC system* with no *loops*, and with at least three *busses* that have at least one *terminal* each. A radial *HVDC system* has exactly one transmission line less than *busses*. Radial systems have the structure of a mathematical tree, as known from graph theory. All *branches* of a radial system need to be transmission lines, as a DC-DC converter *'branch'* would split the *system* into two *systems*, forming one *grid*. Examples are shown in Figure 20.

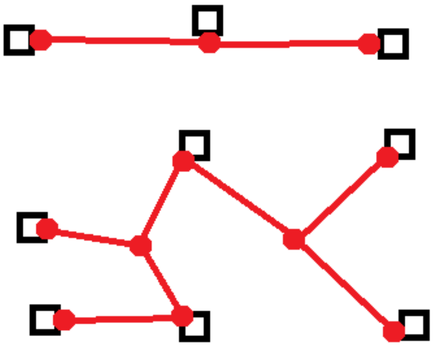

Figure 20: Radial *HVDC systems*

3.2.4 Pseudo-Meshed HVDC System

A *pseudo-meshed HVDC system* is a multi-*terminal HVDC system* with at least one *pseudo-mesh* and with no *controllable meshes* or *meshes*. Examples are shown in Figure 21.

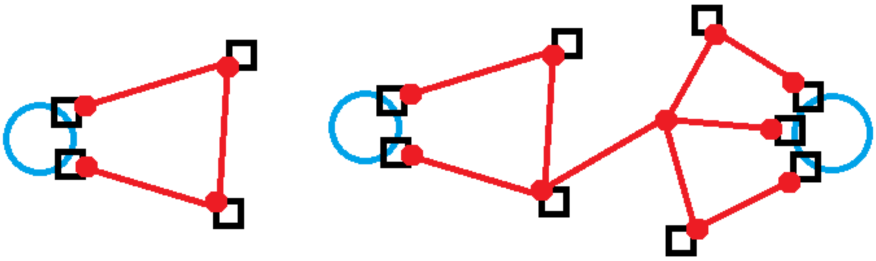

Figure 21: *Pseudo-meshed HVDC systems*

No *pseudo-meshed HVDC system* exists or is planned at the moment of writing.

3.2.5 Controllable-Meshed HVDC System

A *controllable-meshed HVDC system* is a multi-*terminal HVDC system* with at last one *controllable mesh* and with no *meshes*. Examples are shown in Figure 22.

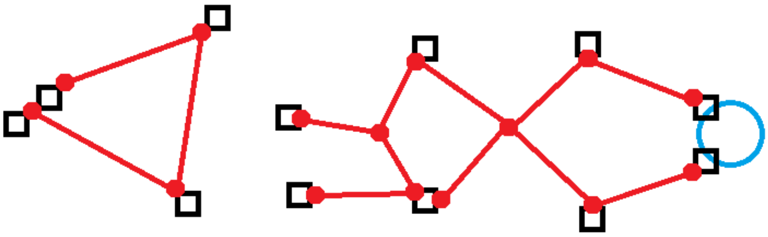

Figure 22: *Controllable-meshed HVDC systems*

No *controllable-meshed HVDC system* exists or is planned at the moment of writing.

3.2.6 Meshed HVDC System

A *meshed HVDC system* is a multi-*terminal HVDC system* with at least one *mesh*. Examples are shown in Figure 23.

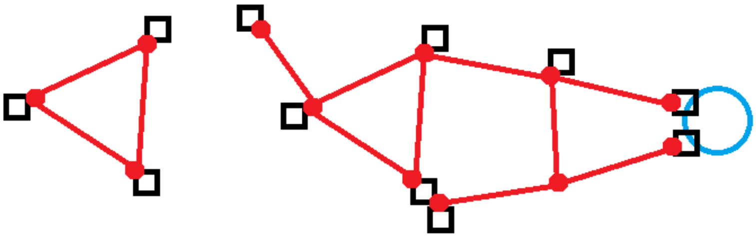

Figure 23: ***Meshed HVDC systems***

No *meshed HVDC system* exists or is planned at the moment of writing.

3.3 *HVDC* System Size

In literature, there is often reference to 'large' *HVDC systems* (e.g. [7]). There are some attributes which are granted to a 'large' *HVDC system*, but there usually is no definition of when a *HVDC system* is large. Some other technical phenomena become relevant only for 'very large' *HVDC systems*, but also here a definition is usually missing.

The terms 'large' and 'very large' are more often used in combination with *HVDC grid* rather than with *HVDC system*. This is mostly based on the general consensus, that large and very large *HVDC networks* will likely be *HVDC grids* consisting of several *HVDC (sub-)systems*.

3.3.1 Large HVDC system

A *HVDC system* can be considered large, if its power flows are so large, that a failure of the *HVDC system* would cause a severe disturbance for the connected AC grids. This especially relates to the primary control reserves of the AC grids. A failure of a line or converter always needs to be acceptable within the security margins, but keeping reserves for the failure of a large *HVDC system* could not be justified. A large *HVDC system* rather needs sophisticated control and protection systems, to avoid this scenario. This indicates advantageous properties of a large *HVDC grid* compared to a large *HVDC system*, since a *HVDC grid* is more robust and has less strict protection requirements.

There is no clear limit when a *HVDC system* can be considered large. However, a simple 'rule of thumb' can be proposed: "A *HVDC system* is large if the sum of all converter power rating is one order of magnitude larger than the power rating of a single converter."

3.3.2 Very large HVDC system

A *HVDC system* can be considered very large, when the power rating of the largest converter station is insignificant compared to the sum of all converter power ratings. In this case all centralised control concepts, where a single converter is operated as slack bus, become questionable. Very large *HVDC systems* are not foreseen in the near future.

There is no clear limit when a *HVDC system* can be considered very large. However, a simple 'rule of thumb' can be proposed: "A *HVDC system* is very large if the sum of all converter power rating is two orders of magnitude larger than the power rating of a single converter."

4 Example: The CIGRE B4 DC Test Grid

The CIGRE B4 DC Test Grid [1] (shown in Figure 24) is given as an example to explain the definitions.

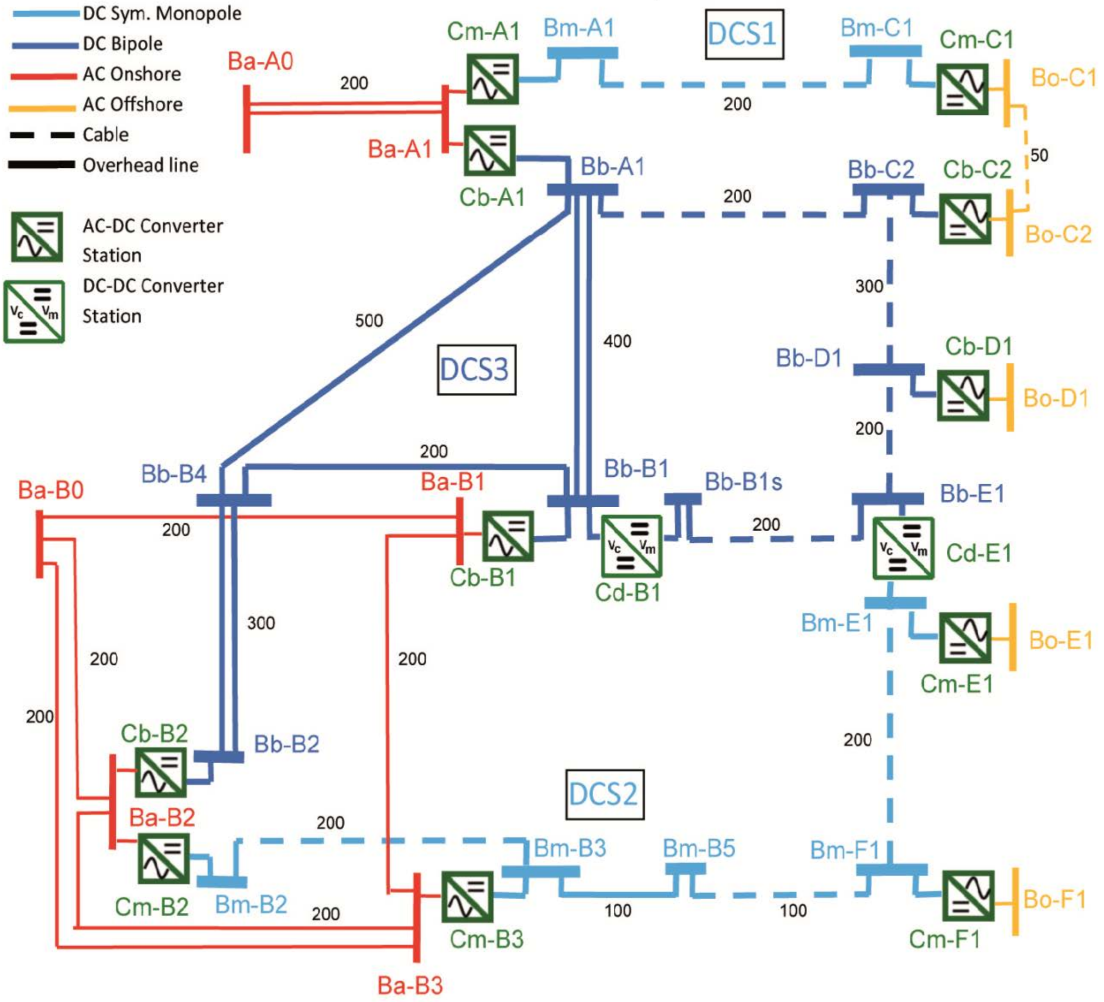

Figure 24: The CIGRE B4 DC Test Grid

It is a *HVDC grid*, consisting of three *HVDC systems* (DCS1, DCS2 and DCS3). DCS1 and DCS2 are displayed in light blue and DCS3 in dark blue.

All AC-DC converters are *terminals*. All transmission lines are *branches*. The DC-DC converter at location B1 is a *branch*, because it is connected to the same *HVDC system* (DCS3) on both ends. The DC-DC converter at location E1 is a dual *terminal* / *branch*. It appears as a *terminal* to both *HVDC systems* at both ends (DCS2 and DCS3) but it appears as a *branch* to the *HVDC grid*.

The *bus* types of the CIGRE B4 DC Grid Test System are specified in Table 1. The *HVDC grid* contains two *supernodes*, at locations A1 and B2. Bus Bb-E1 is a dual *hub* / *node*.

Table 1: *Bus* types of the CIGRE B4 DC Grid Test System

DC *bus*	*Bus* type	*Supernode*
Bm-C1	*Connection point*	No
Bm-A1	*Connection point*	Yes
Bb-A1	*Node*	
Bb-C2	*Node*	No
Bb-D1	*Node*	No
Bb-B4	*Hub*	No
Bb-B1	*Node*	No
Bb-B1s	*Connection point*	No
Bb-E1	*Hub / Node*	No
Bm-E1	*Node*	No
Bb-B2	*Connection point*	Yes
Bm-B2	*Connection point*	
Bm-B3	*Node*	No
Bm-B5	*Connection point*	No
Bm-F1	*Node*	No

The *HVDC systems* DCS1 and DCS2 do not contain *loops*. DCS3 contains a *mesh* and a *controllable mesh*. The *HVDC grid* contains all three *HVDC systems*, and therefore it contains automatically the *mesh* and the *controllable mesh* from DCS3. However, the *HVDC grid* also contains a *pseudo-mesh*, which is formed by the *HVDC systems* DCS2 and DCS3, together with the two *supernodes* A1 and B2. It should be noted, that the *HVDC grid* can contain a *pseudo-mesh*, even though none of its three *HVDC subsystems* contains one (as explained in Section 2.4.3). The *loops* are specified in Table 2.

Table 2: Loop types of the CIGRE B4 DC Grid Test System

Loop type	*Mesh*	*Controllable-mesh*	*Pseudo-mesh*
Involved *busses*	Bb-B1	Bb-B1	Bb-B1
	Bb-B4	Bb-A1	Bb-B1s
	Bb-A1	Bb-C2	Bb-E1
	Bb-B1	Bb-D1	Bm-E1
		Bb-E1	Bm-F1
		Bb-B1s	Bm-B5
		Bb-B1	Bm-B3
			Bm-B2 Bb-B2
			Bb-B4
			Bb-B1

The defined properties of HVDC systems are given in Table 3.

Table 3: *HVDC system* properties

HVDC system	Complexity	Topology	Size
DCS1	Two-*terminal*	Point-to-point	Not large
DCS2	Multi-*terminal*	Radial	Not large
DCS3	Multi-*terminal*	*Meshed*	Large

5 Acknowledgement

This publication is a result of the activities of the North Sea Offshore and storage Network (NSON) Initiative, which belongs to the EERA JP Wind Energy.

6 References

[1] T. K. Vrana, S. Dennetiere, Y. Yang, J. Jardini, D. Jovcic, and H. Saad, "The CIGRE B4 DC Grid Test System," *Electra*, vol. 270, 2013.

[2] M. Szechtman, T. Wess, and C. V. Thio, "A benchmark model for HVDC system studies," *International Conference on AC and DC Power Transmission*, 1991.

[3] G. Asplund, K. Linden, A. Marzin, C. Barker, J. Rittiger, N. Pahalawaththa, R. Iravani, D. V. Hertem, D. Jovcic, K. Soegaard, U. Baur, P. Christensen, P. Labra, M. Rashwan, J. Berteen, S. Cole, E.-D. Wilkening, D. Westermann, C. Yue, and W. Jialiang, "CIGRE WG B4.52 - Technical Brochure 533 - HVDC Grid Feasibility Study," *CIGRE*, 2013.

[4] J. M. Birkebaek, A. Jaederstroem, R. Paprocki, and O. Ziemann, "Using HVDC Links to cope with Congestions in Neighbouring AC Networks," presented at the PSCC, Stockholm, 2011.

[5] N. M. Kirby, N. M. MacLeod, D. Stidham, and M. Reynolds, "Tres Amigas : A flexible gateway for renewable energy exchange between the three asynchronous AC networks in the USA," presented at the CIGRE, Paris, 2012.

[6] T. Nakajima and S. Irokawa, "A Control System for HVDC Transmission by Voltage Sourced Converters," 1999.

[7] C. D. Barker, C. C. Davidson, D. R. Trainer, and R. S. Whitehouse, "Requirements of DC-DC Converters to facilitate large DC Grids," *CIGRE Paris*, 2012.

7 Biographies

Til Kristian Vrana graduated from the Academic School of the Johanneum in 2001 in Hamburg/Germany. He received his bachelor in electrical engineering and information technology in 2005 and his master in electric power engineering in 2008, both at RWTH Aachen University in Aachen/Germany. He achieved his doctoral degree in 2013 at the Norwegian University of Science and Technology NTNU in Trondheim/Norway. Currently he is working as a research engineer in the energy systems department at Sintef Energi in Trondheim/Norway.

Keith Bell is the ScottishPower Professor of Smart Grids at the University of Strathclyde. He joined the University in 2005 having previously gained his PhD at the University of Bath and worked as an electrical engineering researcher in Manchester and Naples, and as a system development engineer in the electricity supply industry in Britain. He is Chartered Engineer, a co-Director of the multi-disciplinary UK Energy Research Centre (UKERC), an invited expert member of CIGRE Study Committee C1 on System Development and Economics and a member of the Council of the IET Power Academy, an initiative to promote electric power engineering as a graduate career in the UK

Poul Ejnar Sørensen received the M.Sc. degree in Electrical Engineering in 1987 from the Technical University of Denmark. In 1987, he was employed as researcher at the Wind Energy Department of Risø National Laboratory. He currently holds the position as professor in Wind Power Integration and Control at the Technical University of Denmark. His research in wind power integration and control include a variety of technical disciplines including power system control and stability, dynamic modelling and control of wind turbines and wind farms, and wind fluctuation statistics. He has many years of experience with standardisation, and is currently the convener of IEC 61400-27 on Electrical Simulation Models for wind power.

Tobias Hennig was born in Meiningen/Germany and received the Master Degree in Electrical Engineering (with distinction) from the University of Duisburg-Essen, Germany. Since 2013 he is working at the Department Transmission Grids at Fraunhofer IWES, Institute for Wind Energy and Energy System Technology in Kassel, Germany. His project works are dealing with power system stability of electrical grids with high penetration of renewable energy sources. His current research interests are planning and operation aspects of large-scale offshore and continental power systems including HVDC applications.

SINTEF

Technology for a better society

www.sintef.no