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Evolution of the HVDC Link Connecting Offshore Wind Farms to Onshore Power Systems

Roland Ryndzionek *  and Łukasz Sienkiewicz 

Faculty of Electrical and Control Engineering, Gdańsk University of Technology, 80-233 Gdańsk, Poland; lukasz.sienkiewicz@pg.edu.pl

* Correspondence: roland.ryndzionek@pg.edu.pl

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Abstract: This paper presents an overview of the DC link development and evolution dedicated to HVDC structure for connecting offshore wind power plants to onshore power systems. The growing demand for the green energy has forced investors in power industry to look for resources further out at sea. Hence, the development of power electronics and industrial engineering has enabled offshore wind farms to be situated further from the shore and in deeper waters. However, their development will require, among other technologies, DC-DC conversion systems. The advantages of HVDC over HVAC technology in relation to transmission distance are given. The different HVDC configurations and topologies of HVDC converters are elucidated. In this context, the HVDC grids are a promising alternative for the expansion of the existing AC grid.

Keywords: HVDC transmission; HVDC; offshore wind energy; DCDC converter; voltage source converter; multi-terminal HVDC

1. Introduction

The growing demand for the green energy has forced investors in power industry to look for resources further out at sea. Hence, the development of power electronics and industrial engineering has enabled offshore wind farms to be situated further from the shore and in deeper waters [1]. Each investment must be assessed in terms of resource evaluation, grid connection and operation, which applies to deep offshore projects, in particular [2,3]. To improve the cost-effectiveness of offshore designs, it will be essential to implement a technology optimizing architecture at a system level [4,5].

Today, wind energy has become the largest form of power generation capacity in Europe with coal been the second. In 2015, the European Union had 142 GW of installed wind power capacity: including 131 GW installed on the shore and 11 GW installed offshore. In 2016, there were 153.7 GW of installed wind power capacity including 141.1 GW installed on the shore and 12.6 GW installed offshore. The total net installed power generation capacity in EU achieved 919 GW in 2016 [6]. In 2017, a record of 3.15 MW net additional installed capacity in offshore wind energy was reached. This was equivalent to 560 new offshore wind turbines across 17 wind power plants [7]. In 2018, Europe connected 409 new offshore wind turbines to the grid covering 18 projects with an additional capacity of 2.649 MW (At the moment there is no official information about 2019) [8].

Moreover, in European Union renewable electricity generation by source (non-combustible) shows a huge increase of wind power. According to the IEA data analysis [9], this is over 100 % since 2010—150 TWh in 2010 versus 360 TWh in 2017. Comparing to the hydro-based energy source, which is constant and is about 300 TWh, wind energy has overtaken all renewable sources [10].

The offshore wind power market is a few times smaller than the onshore market is, so it enables a huge opportunity for investment and future development. To meet requirements, efficiency, security

and market access, wind power plants are moved further and further into the open sea because the grid becomes more demanding.

The main challenge in the development of large offshore wind power projects lies in transmitting power generated by an offshore plant to the onshore electricity grids as efficiently as possible. To reach the full potential of offshore wind power plant (OWPP), new electric connections with improved reliability and efficiency to the onshore grids are required [6].

1.1. Development of Horizontal Wind Power Plants

In wind farms with capacities above 100 kW, mainly horizontal axis wind turbine (HAWT) are used. As a result, a high level of maturity and standardization of technical solutions for this type of construction have been achieved. Scaling the power of the HAWT power plant is relatively simple—increasing the power is achieved by increasing the rotor diameter. With the advances in aerodynamics, materials science and power electronics, it became possible to build a power plant with unit powers of up to 10 MW (Figure 1a,b).

An important stage in the development of wind farm manufacture is at the turn of the 1970s and 1980s and is associated with the search for alternative energy sources due to the fuel crisis. Innovative constructions were designed as part of two projects financed by the US government: high winds project coordinated by NASA and small wind project coordinated by Sandia National Lab. As part of the project implemented by NASA, HAWT turbine designs with outputs from 100 kW to 4.2 MW were developed.

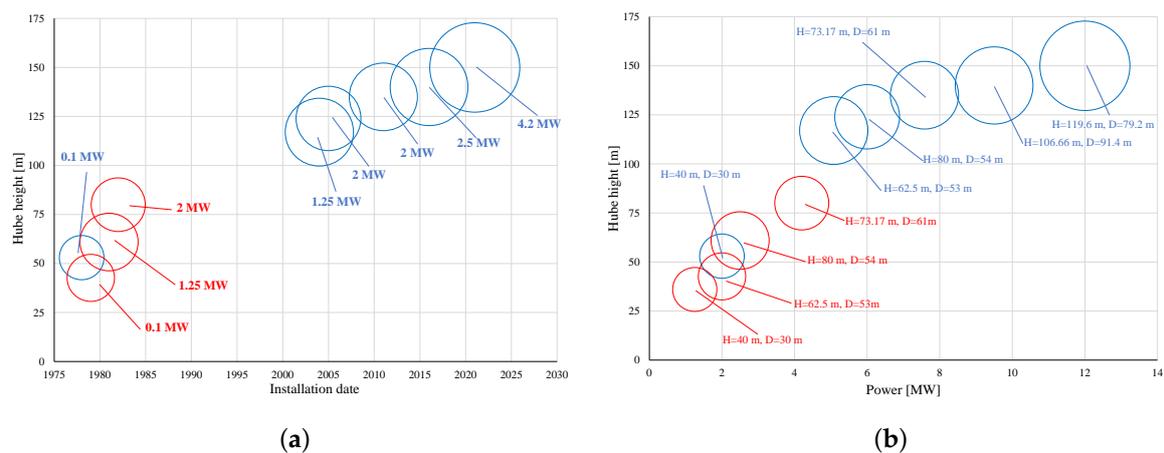


Figure 1. (a) Development of wind power plants with HAWT turbines—date of installation of the largest power plants. Where red color USA, blue color EU. (b) Development of wind turbines with HAWT type turbines—dependence of turbine size (height and diameter) on wind power output. Where red color USA, blue color EU.

In the 21st century, the leaders in the field of wind farms with HAWT were European companies (REpower, Vestas, Enercon, Siemens) (Figure 1a). Synchronous generators (either singular or multiple) are the primary input of electrical energy [11]. Wind farms have started to be located offshore, where at a lower height of towers better wind conditions can be obtained. Currently, the wind plant capacity increase is achieved by increasing the active surface of the turbine (blade lengths up to 107 m).

1.2. DC Grids Requirements

The HVDC requirements have been determined based on [12]. The main data are presented in the Table 1.

Table 1. Requirements for low, medium and high power HVDC grids.

Parameter	Classification	Range
Transferred DC Power	Low	$P_{dc} < 50 \text{ MW}$
	Medium	$50 \text{ MW} < P_{dc} < 500 \text{ MW}$
	High	$500 \text{ MW} < P_{dc}$
Transformation Ratio Vdc-high/Vdc-low	Low	$1 < \text{Ratio} < 1.5$
	Medium	$1.5 < \text{Ratio} < 5$
	High	$5 < \text{Ratio}$
HV side DC Voltage	Medium	$V_{dc} < 100 \text{ kV}$
	High	$100 \text{ kV} < V_{dc}$

Offshore wind power market has a complex supply chain, thus millions of EUR investments in it create thousands of new jobs. Based on the European Wind Energy Association, there are around 75,000 jobs directly related to offshore wind power in Europe [13,14]. The growth of this sector creates also opportunities to develop and attract the investors to remote cities in Northern Germany, Denmark and the United Kingdom, e.g., ports of Cuxhaven and Bremerhaven, Mostyn and Grimsby in the United Kingdom where the wind power becomes the main sector of the local economy. The number of projects under development demonstrates great potential for further growth of this sector [14,15].

In this work the authors give an outline of HVDC transmission systems bridging offshore wind power plants with onshore power system. This review takes into account different existing and researched technologies of converters used in HVDC. The advantages of HVDC over HVAC technology in relation to transmission distance are given in Section 2, where also a new break-even-distance for offshore installations is demonstrated. The different HVDC configurations and topologies of HVDC converters are explained in Section 3. Finally, possible development paths and future solutions for integration of OWPPs are suggested in Section 4.

2. HVAC vs. HVDC

The HVDC transmission has been used for many years thus the technology is mature. Particularly over long distances, it has great advantages over HVAC. The advantage of DC-DC converter topologies amid existing AC solutions for longer distance transmission has been established in literature [16,17]. The most desirable advantages of HVDC transmission line in contrast to AC line cover: absence of the skin effect; reduced transmission losses particularly for long, high voltage applications due to lack of reactive charging currents; cheaper and less demanding manufacture process of DC cables, especially for long and ultra-high voltage DC cables and higher degree of active power control.

The main drawback of HVDC vs. HVAC transmission, which is the high cost of power electronic terminals, is still valid. Nonetheless, the gradual adoption of cheaper and more efficient transistor modules (e.g., SiC) in recent years may shift the balance in favour of DC transmission [18,19].

Before large-scale offshore wind farms were built, HVDC offshore transmission lines were constructed. In general, more than 60 DC stations, and 52 of which are HVDC, have been built since 1960 in Europe (including a project which will be launched in 2020). It is worth emphasizing the fact that in the last 5 years as many as 26 stations have been launched [20]. Which represents 40 % of the stations built.

It is clear that some stations have been closed and some have been modernized and upgraded. Nevertheless, the number of recent projects gives a picture of how fast the DC industry is growing. Chosen DC-DC interconnections have been presented in Table 2.

Table 2. A selection of HVDC transmission lines in Europe [20]

Name	Link	Total km	Voltage (kV)	Power (MW)	Year
Baltic Cable	Germany–Sweden	262	450	600	1994
SwePol	Poland–Sweden	245	450	600	2000
Italy-Greece	Italy–Greece	310	400	500	2001
NorNed	Netherlands–Norway	580	450	700	2008
BritNed	UK–Netherlands	245	450	1000	2010
NordBalt	Sweden–Lithuania	450	300	700	2015
DoIWin2	Germany–Germany	135	320	900	2016
Western HVDC Link	UK–UK	422	600	2200	2017
ElecLink	France–UK	70	320	1000	2019
Caithness Moray HVDC	France–UK	70	320	1000	2019
NORD.LINK	Norway–Germany	623	525	1400	2020
NSN Link	Norway–England	730	515	1400	2020

The general approach which can be observed for a few years in the power industry is to develop an integrated system to fully utilize the potential of the wind farm and provide savings in space [16,21]. HVAC has the advantage to operate with relatively inexpensive terminals whereas HVDC needs to apply quite costly power converter stations. Moreover, for long distances (like in the case of remote offshore locations), the extra cost of power converters is counterbalanced by cost savings on cheaper DC cables and smaller transmission losses [22]. Additionally, HVDC cables (especially utilizing cross-linked polyethylene as an insulation) have less weight than regular cables. Thus, it is possible to transport longer sections of cable, due to the lower ratio between weight and unit length [23]. The DC transmission systems offer a more cost-effective choice than AC transmission systems when remote, high power delivery is concerned. Such critical distance is called a break-even-distance (Figure 2). In such context, the development of an offshore grid would be particularly beneficial.

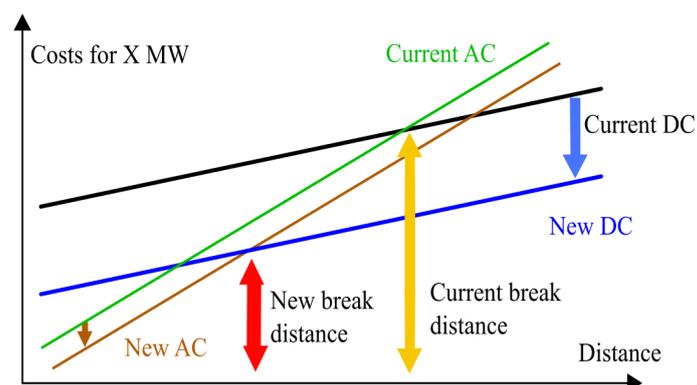


Figure 2. AC vs. DC break-even-distance for a large power wind farms [24–26].

The use of direct current for higher power wind plants to suggest a lower price point is very challenging (DC-DC converter cost being a crucial factor) (Figure 2). The distance depends on several factors (both for lines and cables) and analysis must be made for each individual case [27]. For HVDC onshore transmission line the break-even-distance is approx. 600–800 km [24,25]. However, the break-even-distance is much smaller for sub sea cables (typically about 50 km) than for an overhead line transmission [28]. In general, new OWPP are built more than 100 km from shore [26].

3. HVDC Offshore Technologies Comparison

The HVDC transmission systems are among the basic elements of future-oriented intelligent power grids referred to as Smart Grid. The development of such a network is aimed at increasing system security and energy efficiency through the use of modern equipment and the integration of renewable sources. In general, HVDC systems are implemented by means of a transmission system consisting of converter stations and a DC cable line. Currently, there are a number of layout configurations available, which can basically fall into two groups: Back-to-Back layouts (BtB) and systems for long-distance power transmission.

The “oldest” and most popular are solutions based on thyristor, called Line Commutated Converters (LCC), also known as “classical HVDC”. Newer systems are based on transistors and are called Voltage source converters (VSC) [29]. Both systems require an expensive HVAC transformer’ platforms (represented by blue color in the following figures) and HVDC platforms (represented by blue orange in the following figures), AC and DC filters, converter valves and the control system. The typical HVDC scenario used for linking of OWPP with onshore power system is shown in Figure 3.

Wind turbine transformers step up the voltage from 690 V typically to 25–40 kV, as higher voltage transformers would be too large to fit into the tower cross-section. The typical power rating of the turbine side converter is 5–10 MW. Collection systems mostly utilize the 33–36 kV AC to gather the energy from the wind farm [5,30]. High voltage submarine cables connect the wind turbine output to the offshore platform. High voltage transformer at the offshore platform steps up the collection system voltage to the level of 132–150 kV (in some OWPP even 400 kV) for transmission and interconnection to the onshore grid by DC line, which is typically 320 kV [28,31,32].

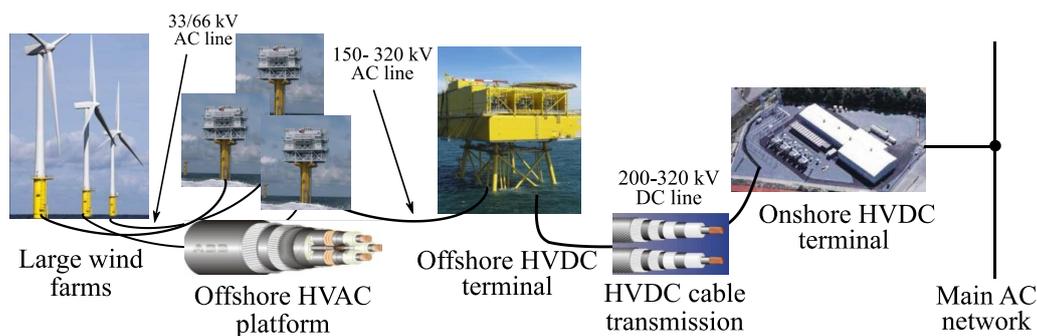


Figure 3. Common scenario for connecting offshore wind power to main ac network utilizing HVDC technology.

The largest players in the HVDC industry who invest in network development are: ABB, Siemens and Alstom Grid (since 2017 GE Grid). Chosen HVDC offshore wind power plants in Europe have been presented in Table 3.

Table 3. A selection of HVDC offshore wind power plants in Europe [20]

Name	Power [MW]	AC / DC Voltage [kV]	DC Submarine/Underground Cable [km]	Year
BorWin1	400	170/150	2 × 75/2 × 125	2009
SylWin1	864	-/320	2 × 159/2 × 45	2014
DolWin2	916	155/320	2 × 45/2 × 90	2015
BorWin2	800	380/300	2 × 125/2 × 75	2015
HelWin2	690	-/320	2 × 45/2 × 85	2015
Nordsee Ost	422	155/250	2 × 57/2 × 20	2015
DolWin3	690	170/320	2 × 45/2 × 85	2017
BorWin3	900	380/320	2 × 130/2 × 30	2019

3.1. Line Commutated Converters

LCC converters technology is well known and mature (Figure 4). The advantage of LCC converters is their large operating experience and relatively low price. Thyristor based converters are characterized by high voltage even 600 kV and high power ratings. The thyristor technology required a strong AC grid and active power control.

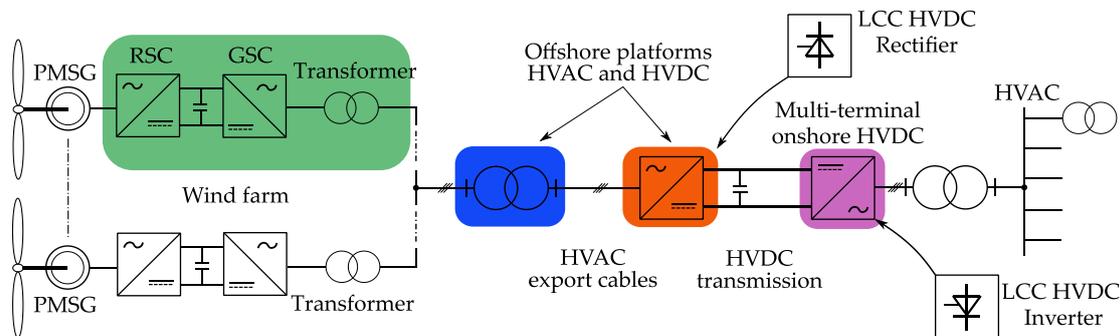


Figure 4. Detailed view of offshore wind power transmission schematics based on LCC HVDC technology (where RSC—rotor side converter GSC—grid side converter, PMSG—permanent magnet synchronous generator).

Broad use of transistors revolutionized the HVDC technology, which in turn rendered the LCC as less viable for offshore applications.

3.2. Voltage Source Converters

The development of power semiconductors, including fully controllable devices such as GTOs and IGBT transistors, has driven the use of the voltage source converter (VSC) in HVDC systems. The two-level converter has been developed in 1997 [33]. Since 1999, the voltage source converter with IGBT transistors has been widely used as a HVDC terminal. This solution has been applied in the first HVDC commercial project with offshore wind power plant [34,35].

The VSC technology in HVDC systems (Figure 5) has many advantages like compactness, black-start capability, the capability to connect to weak AC networks, independent control of active and reactive power [36–40]. Consequently, it has become the preferred HVDC converter technology for connecting OWPP e.g Borwin1 by ABB (2009, 400 MW, 125 offshore + 75 onshore km), Sylwin1 by Siemens (2014, 864 MW, 159 offshore + 45.5 onshore km) and DolWin3 by Alstom (2017, 900 MW, 84.5 offshore + 76.5 onshore km).

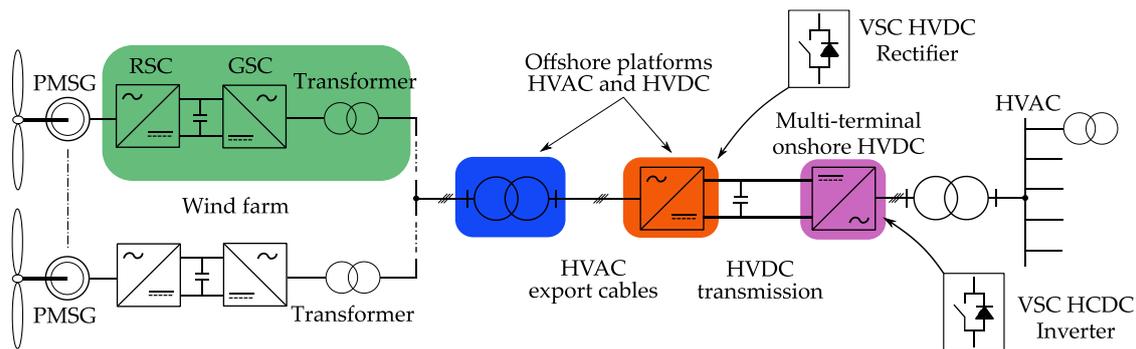


Figure 5. Detailed view of offshore wind power transmission schematics with VSC-based HVDC technology—Point-to-point connection (where RSC—rotor side converter, GSC—grid side converter, PMSG—permanent magnet synchronous generator).

Over time, the VSC technology has been evolving. The three-level PWM controlled converters have been developed. Moreover, the converters become more efficient due to the development of transistor technology (Si IGBT power modules). After that, many attempts were made to invent three or multi-level topology and apply it in HVDC [29] e.g., neutral point clamped converters (NPC) and its variety - 3L-ANPC, 5L-HNPC, CHB or diode-clamped converter (DCC). However, only NPC were adopted broadly by the industry (Figure 6a). The developments of the three-level converters resulted in reduced harmonic generation, reduction of losses to approximately 1.7% and full control of offshore grid's dynamics.

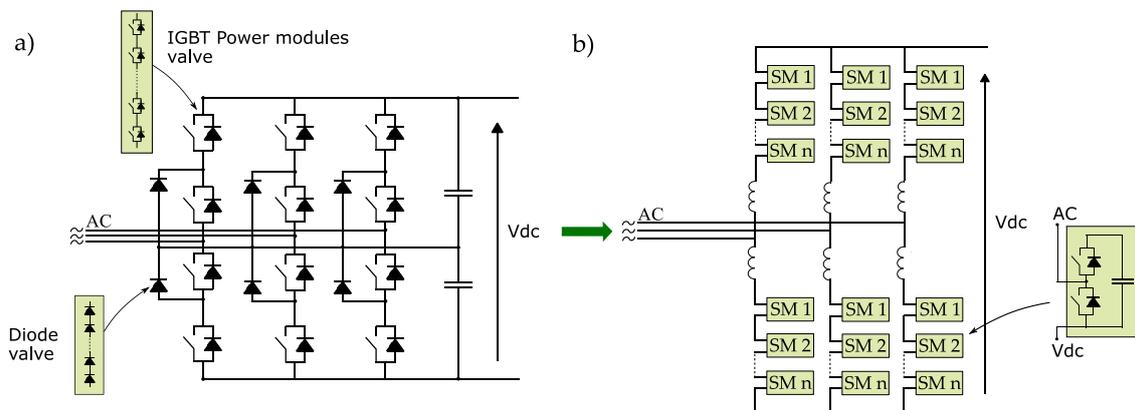


Figure 6. VSC HVDC technology (a) the NPC three level converter, (b) MMC—Modular Multilevel Converter.

An example of a modern multilevel structure is a Modular Multilevel Converter (MMC) (Figure 6b). This topology was developed in the early 2000s and received increased attention since then [32,41]. MMC converters are the preferred technology in today's VSC-HVDC. The MMC is a type of cascaded multilevel converter which is based on series connection of sub-modules (SMs). Single SM is composed of a half-bridge converters connected in series.

The advantage of the MMC is possibility to generate a staircase voltage waveform. The shape of this voltage depends on number of SMs used in specific topology—more SMs give a more sinusoidal waveform [42,43]. However, to simplify the deployment of OWPP, new strategies to reach higher efficiency and better reliability of the converters are necessary to be developed. Moreover, using a higher voltage will reduce transmission losses [44].

3.3. HVDC Diode Rectifier Unit

In last few years the new type of solution based on diode rectifier unit (DRU) has been under investigation. This concept was called “2nd generation DC grid access for offshore wind farms” by Siemens [45,46]. The main idea is to replace the AC by an AC-DC offshore substations, directly linked with the turbines (Figure 7).

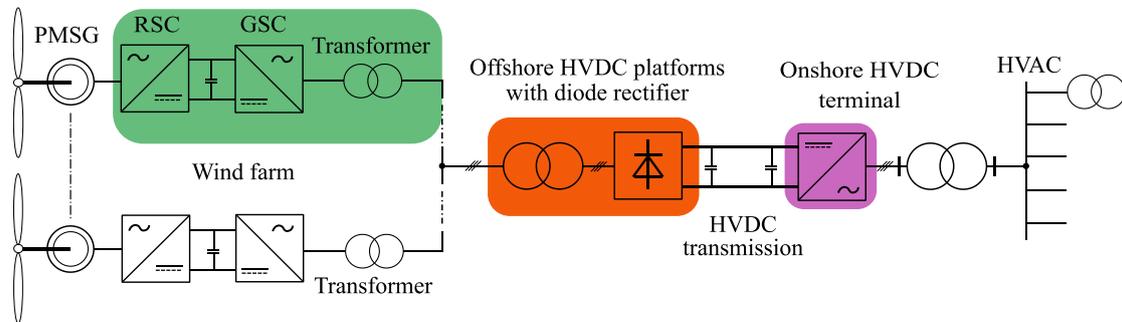


Figure 7. The HVDC transmission topology based on the diode rectifier (where RSC—rotor side converter GSC—grid side converter, PMSG—permanent magnet synchronous generator).

First and foremost, HVDC diode rectifier offers reduced costs and increased reliability due to the lack of offshore DC converter as a unique malfunction location. Moreover, using distributed small DC platforms it is possible to achieve high reliability, low maintenance efforts and most important—small platforms with easy transport and installation. A diode is the simplest and the most robust semiconductor in power electronics. Using diodes instead of transistors (as in VSC) leads to lowering the number of auxiliary components such as: dc breakers, discharge resistors, gate drivers [47]. Going further, the simplest solutions are desired and that could be realized by a diode rectifier. The main premise of DRU is the simplicity of distributed DC platforms without sacrificing the robustness [48,49].

In literature, 6-pulse or 12-pulse diode rectifiers are commonly described (with 18 and 24 pulse present as well [46,50–53]). The first is built as a 6 pulse diode bridge consisting of six uncontrollable diodes and a low-pass filter for smoothing the DC current [54]. The second is formed by dual 6-pulse diode bridges joined in series and feeding a common DC bus, together with a special three-winding transformer (with secondary voltages in 30 degrees phase shift) at the supply side of the rectifier. The HVDC link will comprise three 200 MW diode rectifier converters with their outputs constituting a 640 kV pole-to-pole DC link to be connected to the onshore DC/AC power conversion station (Figure 8).

The diode rectifier is combining the active module of a transformer with a 12-pulse DRU and additional equipment which simplifies the topology and reduces the quantity of electric components, particularly on high voltage side. Moreover, in contrast to thyristors, diodes do not need guarding against the high current deltas at start-up, are less sensitive to failure within the recovery period nor do they require extra effort for installing and diagnostics [55,56].

However, this solution has some drawbacks which have to be investigated. The main issue is that the DRU is a non-controllable device. In this case, the OWPP AC system has to be controlled by the wind turbine. Moreover, various wind turbines and OWPP topologies are required. A DRU is not able to provide reactive power, needing power converters or other devices to compensate it [46]. In large scale, a DRU concept may be a key factor in determining, if offshore wind farms are commercially viable [27,45,57,58].

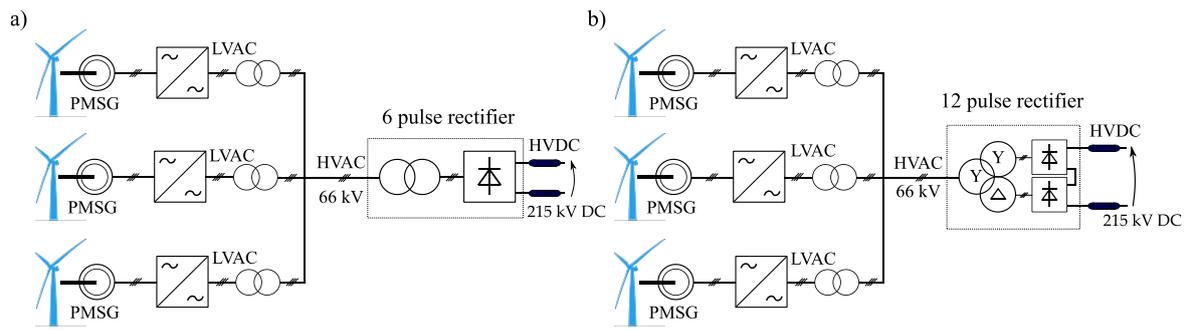


Figure 8. The schematics of (a) 6-pulse and (b) 12-pulse diode rectifier HVDC links.

3.4. Hybrid LCC/VSC Schemes

The hybrid topology (Figure 9) is developed in parallel to VSC technology and is defined as a mix of topologies described in previous chapters. The main benefits that come from such approach are lower losses compared to pure VSC (due to the LCC switching mechanism) or fact that many VSCs can be connected to a single LCC which may represent a more economic and robust investment (less switching devices). The hybrid topology has disadvantages such as managing of a DC link’s discharge for reversed power flow [59–61]. Moreover, some aspects of the hybrid technology are technically challenging: higher insulation requirement on the wind turbines, selected electrical equipment of the WPP must be oversized to prevent over-voltages from occurring in the turbines [62].

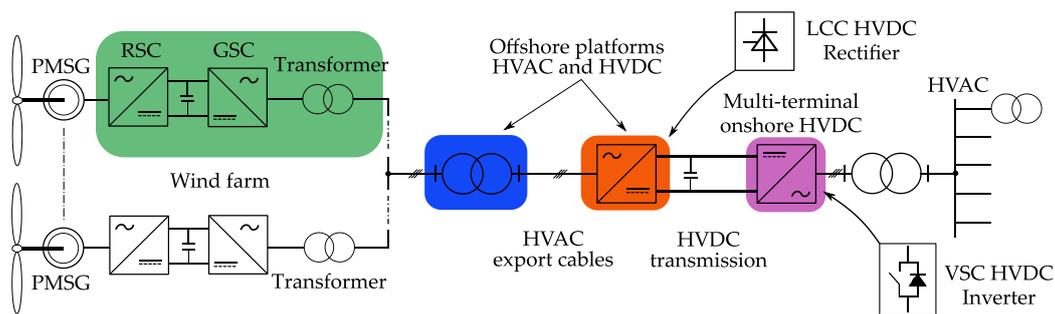


Figure 9. General overview of the HVDC hybrid transmission system based on VSC and LCC technology [60].

In literature a various configurations are developed. The interesting solution is reported in [63,64] which described a hybrid topology of the 12-pulse diode rectifiers and a VSC (Figure 10). The 12-pulse diode rectifier is able to deliver a large amount of the OWPP output power, which is decreasing the necessary power rating of the VSC.

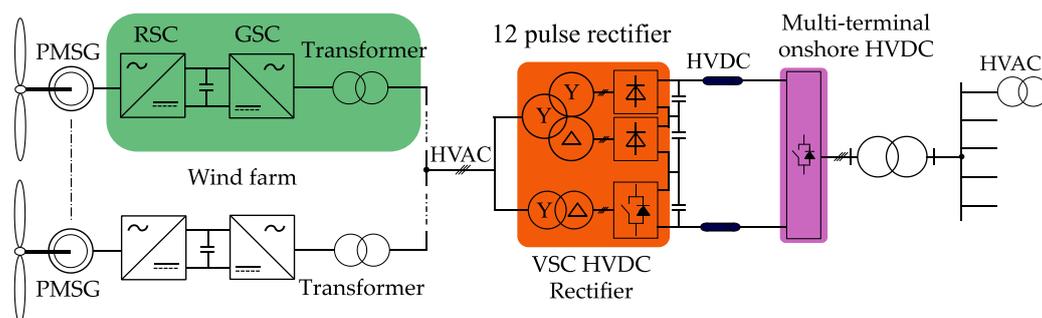


Figure 10. General overview of the HVDC hybrid transmission system [63].

The VSC generates the onshore AC voltage at the constant magnitude and constant frequency. In addition, the VSC is able to compensate for the 11th and 13th order current harmonics due to the 12-pulse diode rectifier (an active power filter operation). The calculated efficiency is 99.07 % and cost of power devices is 53.47 % of VSC HVDC system [65]. Finally, this system will fit in the same size as VSC HVDC stations.

3.5. Costs Comparison

In Figure 5 Point-to-point connection has been presented. This kind of a connection is the most straightforward HVDC offshore wind farm configuration. However, the new concepts and topologies, described in the preceding paragraphs, are being developed. In [66] a detailed cost analysis for different DC offshore collections grids has been performed. In Figures 11 and 12 cost and different configurations of modern DC-DC offshore wind farm have been presented. The viability analysis deals with the assessment of the total cost of a OWPP with the complete transmission system. These results present a starting point for the comparison between AC and DC OWPP plan profiles and enable a decision which one is the most cost-effective.

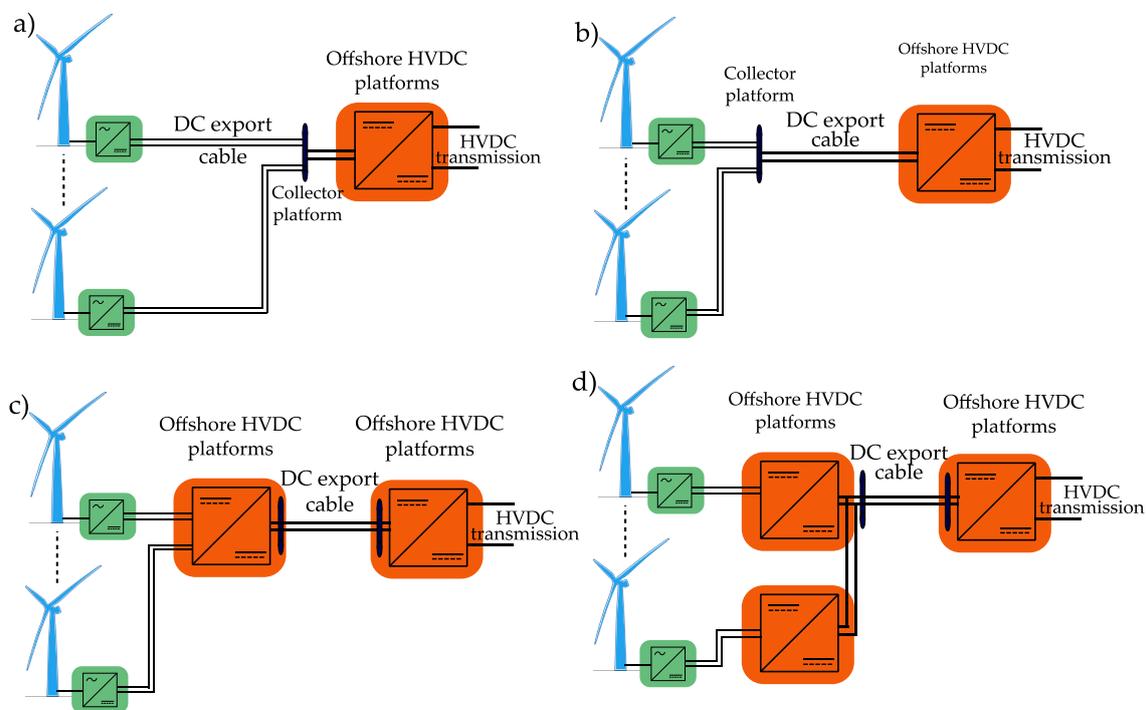


Figure 11. The proposed DC OWPP configurations: (a) DC1, (b) DC2, (c) DC3, (d) DC4.

The DC1 is a configuration where there is a straight connection between turbine feeders and the HVDC main substation, the DC2 represents an offshore grid where wind turbines' strings are linked to a common offshore aggregation location, the DC3 is a configuration with two step-up DC-DC offshore converters and the DC4 is a configuration with one single step-up DC-DC converter for each turbine feeder.

The DC-DC converters, wind turbines and platforms are the main factors in the total unit cost of an OWPP. Optimization of number and location of DC-DC converters along with the improvement of the converters' efficiency is required during the design of an OWPP [66]. Each of the analyzed scenarios offers comparable unit cost to a classic point-to-point configuration, while DC4 presents the highest capital cost, which is above the reference level. The main differentiation is, however, the cost associated with energy losses.

It is noticeably lower for DC1 and DC2 and comparable with point-to-point reference for DC3 and DC4. The last two scenarios possess the advantage of a higher level of control due to a larger number of converters.

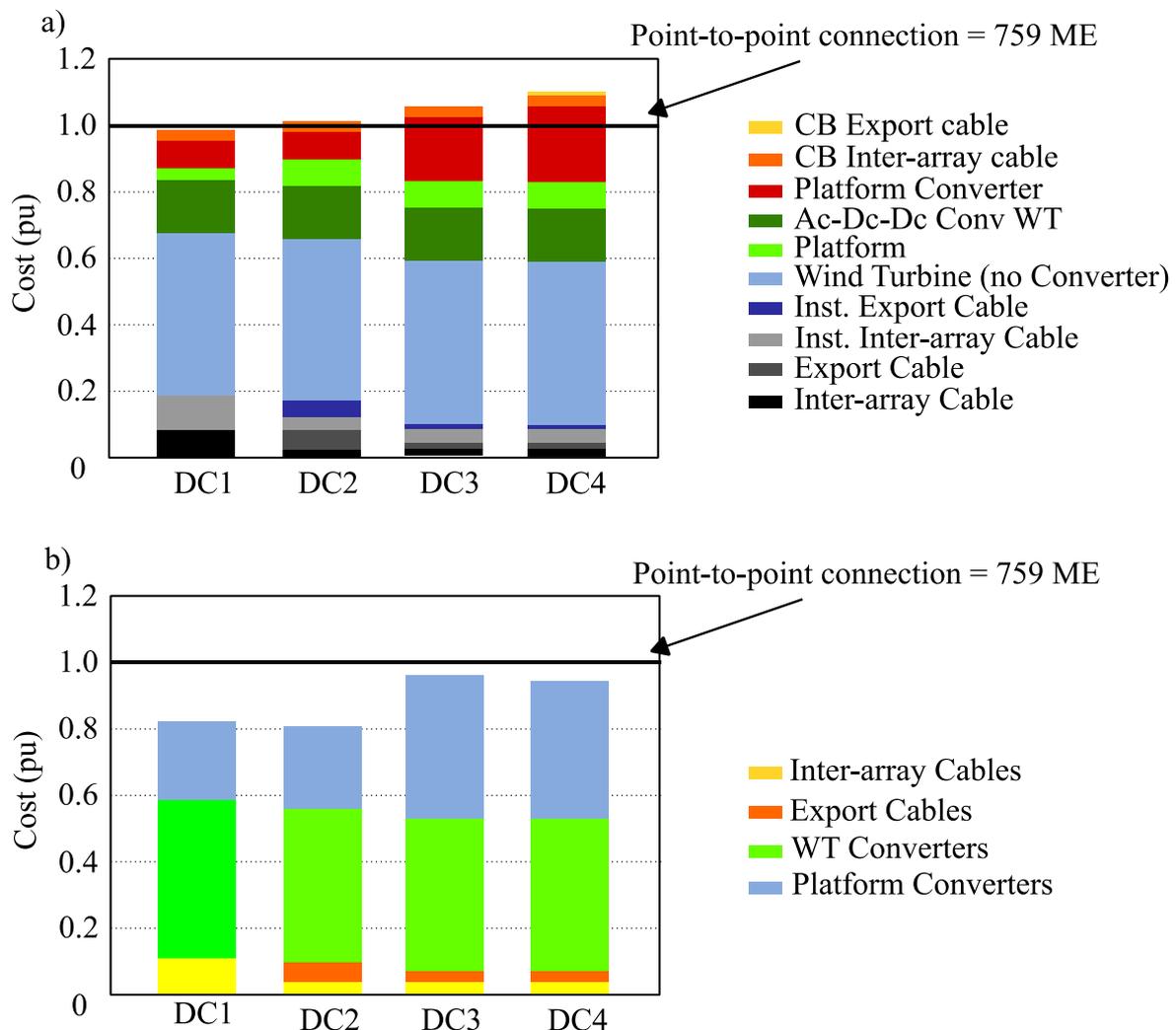


Figure 12. Breakdown of the DC OWPP configurations: (a) Capital costs, (b) Costs associated with energy losses [66].

4. More Offshore WPP—Emergence of a Super Grid

In recent years several new topologies of offshore power grids have been proposed as an outcome of simulations, economical and technical studies. A term common for those works is a super grid. According to the definition, a super grid is a wide-area transmission network which enables the trade of high amounts of energy between remote locations. The main concept of a super grid is to improve the security of supply of linked networks and aid the extensive connection of renewable energy sources directly to DC networks [30].

In [67] two main scenarios for future development of European network transmission system have been published. The authors claim that by the year 2030, 13% of renewable electricity is produced from solar and 28% from wind energy. In 2040 17% of the renewable electricity is generated from solar and 41% from wind, giving 58% in total. Those predictions for increasing contributions of renewable energy sources, give a strong basis to believe in the dynamic development of HVDC low loss networks, as well.

In 2016 the “Paris Climate Agreement” has been signed [68]. In general, 195 countries have committed themselves to reducing the pollution and increasing the role of renewable, sustainable energy sources. However, this document also points to reducing capital costs of new installations. Thus, the idea of a HVDC Grid Interconnector has appeared in response (Figure 13). Those interconnectors are special platforms connected to each other by high capacity DC cables. The platforms are called hubs. The role of grid interconnectors is to transfer the power generated by OWPP to different sites linked in a clever and organized form. Finally, it is expected that the hubs will power surrounding infrastructure using the Power-to-X conversion (P2X), instead of the offshore converter platforms.

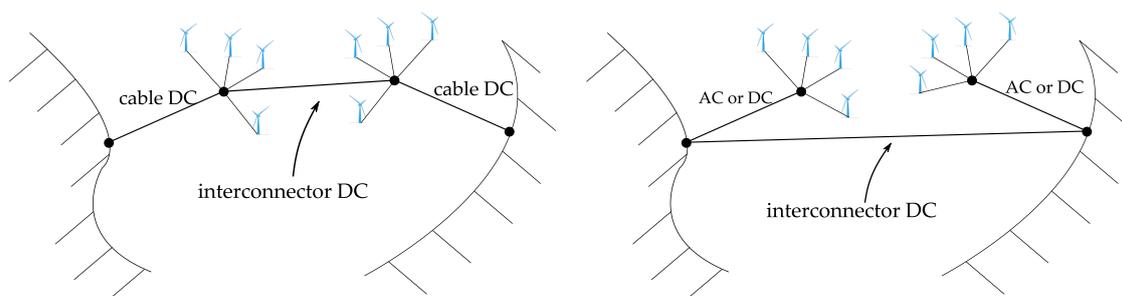


Figure 13. Selected scenarios of hubs integration.

Another possible evolution path is when DC hubs will become Multi-terminal HVDC (MTDC, Figure 14). In such scenario multiple OWPP can be connected to multiple AC systems. The research shows that challenges according to operation and control of MTDC are similar to challenges present in HVAC systems e.g., power sharing, voltage control and power flow control. Similarly, the detailed modeling of power converters is required for assessment of the dynamic behavior of such a grid. In the future, MTDC transmission may help to reduce the number of converters, the capital cost of new installations and switching losses[69–71].

There are three main players currently in the European market, each with different approach to a MTDC concept: HVDC Light (ABB), HVDC Plus (Siemens) or HVDC MaxSine (Alstom Grid/GE) [72]. That is why it is so important to develop a uniform system to allow any number of connections between OWPP, hubs, AC grid, etc. Therefore, ongoing European projects fueling further research are necessary in developing future standards (concerning uniform HVDC technology, grounding topology and the voltage level, amongst others).

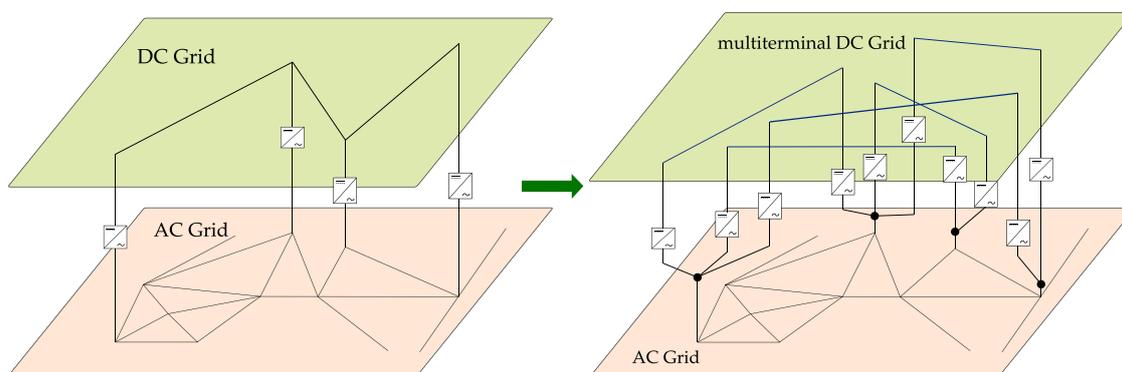


Figure 14. Proposed transition from current HVDC to MTDC grid.

The most viable scenario is that the super grid will be developed in a natural way, taking in to account already existing HVDC grids, like interconnectors, offshore links to wind farms, oil and gas platforms. A different path is to take advantage of energy storage devices for the energy produced by the wind farms (P2X case).

Power-to-X or P2X is a concept relying on conversion of electricity into an energy carrier in a form of heat, product or basic substance. It is a broad term for different ways of generating energy, namely power-to-gas, power-to-liquid, power-to-fuel, power-to-chemicals, power-to-heat and power-to-mobility. P2X provides the possibility to create long-term storage options and substitute hydrogen, methane and other synthetic fuels for fossil energy sources in transportation, chemical processing and heat production.

Disadvantages of P2X combined with OWPP include high investment costs and energy losses due to low overall efficiency of conversion process. Several authors conclude that in P2G case, hydrogen produced from wind energy should be sold, as re-electrification is exceptionally expensive. Future research works should be focused on the reduction of implementation and maintenance costs for the P2X to become a viable scenario of OWPP integration [73–75].

Another scenario addressing the intermittency of renewable energy sources might be compressed air energy storage (CAES) coupled with an OWPP. An interesting implementation of such approach is FLASC project, where energy is stored using a hydro-pneumatic liquid piston, driven by a reversible pump-turbine. The FLASC is exploiting the hydro-static pressure of the deeper sea region to preserve a stable pressure in the CAS, which is independent of the state-of-charge. As it integrates into an existing offshore floating platform framework, it is treated as a viable solution.

The project created by University of Malta is currently at the stage of a large-scale demonstrator at the open sea [73,76].

5. Conclusions

The increase in participation of HVDC technology in modern power systems is strongly related to the development of power electronic devices across the last decades. The nominal parameters of modern HVDC systems reach MV of DC voltage, tens of GW of installed power while improving on the reliability and robustness of the built systems. In addition to the well-known LCC topology (which remain to represent the largest share of the converters used in the HVDC transmission market), there is an increase in the number of VSC MMC topology applications. Moreover, hybrid topologies, which are derivatives of Modular Multilevel Converters, are currently under intensive development.

The development of new offshore wind power plants has slowed down slightly according to data from 2018 (partly due to the increased interest in the Photo-voltaic farms) [8]. Nevertheless, new OWPPs are still being built, e.g., Thor—2020 Tender with 1000 MW capacity. Only high power OWPP are currently constructed to adjust to the evolving energy market. To follow those trends, the offshore energy market will promote innovations in the HVDC technology. This will provide more stable and greener OWPPs offering a higher degree of controllability.

Authors believe that the development of offshore wind power plants, an increasing number of DC transmission systems including classic point-to-point HVDC, DC hubs and multi-terminal HVDC will create a DC super grid in the future. This claim is evidenced by a noticeable intensification of research work concerning those complex systems.

The paper shows that technological advancements in the last 10 years enable higher water depths and increased distances to shore for new OWPPs. The new break-even-distance for offshore installations is proposed. The advantages of HVDC over HVAC technology in relation to transmission distance are given. The authors attempt to describe and summarize the HVDC offshore transmission. The different HVDC configurations and topologies of HVDC converters are elucidated. Finally, the future solutions and possible development paths are also suggested.

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