VSC-HVDC technology on power systems and offshore wind farms integration

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Abstract. This work presents an analysis of the VSC-HVDC technology in power systems since it was implemented experimentally in the late nineties to the present. On the other hand, the main features of offshore wind farms integration using VSC-HVDC technology will be explained attending to current projects in operation and those under study/construction.

Key words: VSC-HVDC, offshore wind farm, inner array grid, interconnections.

1. Introduction

Over last century high voltage alternating current (HVAC) has been used in most of transmission and distributions systems. Nevertheless, high voltage direct current (HVDC) systems were implemented in bulk power and long distance transmission lines, where technical and economic advantages over alternating current were achieved.

In 2009 European Union established new energy policy supporting several ambitious goals related with greenhouse gas emissions, renewable energy, energy efficiency and electricity interconnectors between European network systems. 2009/28/EC directive demands member states to develop an own National Renewable Energy Action Plan (NREAP) in order to achieve required targets. However, in 2014 European Commission set up even further objectives under “European Energy Security Strategy” document strengthening following targets: reducing energy dependency from external countries, increase Europe´s security of supply, 27% renewable energy in 2030 and use indigenous primary energy sources [1].

According to this new plan in Europe, it is clear new technologies are needed to fulfil main requirements of future transmission network, e.g.:

- Higher transmission capacity over large distances with low losses.
- Possibility of interconnectors between five different asynchronous region groups in Europe.
- Integration of large scale renewable production energy systems.

Bearing all these issues in mind, this work is divided into following chapters. Second chapter is focused on VSC-HVDC applications on power system (interconnectors and oil/gas platforms electrification system). Third chapter shows integration of large scale offshore wind farms in North Sea using VSC-HVDC technology. Nowadays developers use different topologies and schemes will be described including internal architecture. The currently offshore wind farms are analyzed. Finally some conclusions will be mentioned.

2. VSC-HVDC technology

There are two different HVDC technologies currently used for transmission systems, depending on converter topologies. Line-Commutated Converters (LCC) using thyristors and Voltage Source Converters (VSC) using IGBT are both implemented around the world on power systems. VSC converters have some advantages over LCC converters [2] [3]:

- Reactive and active power can be independently controlled.
- Reactive power can be controlled at both AC sides, VSC converters can absorb/produce it.
- Switch frequency can be smaller with low losses, currently about 1% per VSC converter.
- Multi-terminal DC grid systems can be achieved because VSC converters don´t need change polarity in DC node if active power flow must be changed.
- Higher voltage waveform quality, so filters (if necessary) could be smaller because harmonics levels are lower.
- Smaller footprint in VSC substations, around 40% compared with LCC ones.

At present only four suppliers monopolise VSC-HVDC converters´ market under different denominations. HVDC Plus was developed by Siemens, named MaxSine by joint venture General Electric and Alstom Grid both based on MMC (Multi-Modular Converter) while ABB took slightly different technique based on CTL (Cascaded Two Level) converters [4]. In China C-EPRI launched VSC-HVDC technology called HVDC Flexible.

A. Point-to-point VSC-HVDC transmission systems and multi-terminal VSC-HVDC schemes

A point-to-point VSC-HVDC transmission system consists in two converters linked by DC line between two AC grids. One of the most important features of VSC-HVDC system is that the DC side voltage polarity doesn´t change even when the direction of power flow must be changed. Since polarity reversal is not necessary in VSC converters extruded insulation cables are widely used in DC systems [5].

Since first VSC-HVDC commercial project was commissioned in 1.999 in Gotland Island, different converter topologies have been developed aiming low losses in the valves of converters. Basically high losses on VSC converters occurred because of high switching frequency applied to IGBT devices. This development was carried out by ABB cutting down losses from 3% in 2 level converters topology to 1% in CTL or MMC topologies. In Table I VSC-HVDC transmission systems in operation are shown according to developers released reference projects [6-8].

TABLE I.-VSC-HVDC projects in operation

Project	Power (MW)	Distance (km)	Converter topology	Voltage (kV)
Hällsjön	3	10	2 level	±10
Gotland	50	70	2 level	±80
Tjaereborg	7	4,3	2 level	±10
Directlink	3x60	65	2 level	±80
Murraylink	220	180	3 level-ANPC	±150
CrossSound Cable	330	40	3 level-ANPC	±150
Estlink 1	350	105	2 level (OPWM)	±150
Caprivi Link	300	950	2 level (OPWM)	-350
East-West Intercon.	500	262	2 level (OPWM)	±200
TransBay Cable	400	85	MMC	±200
Skagerrak 4	700	240	MMC	+500
Inelfe	2x1.000	65	MMC	±320
Xiamen Island	1.000	10,7	MMC	±320
NordBalt	700	450	MMC	±300
Aland Link	100	158	MMC	±80

Most of VSC-HVDC projects in Table I use DC-XLPE cables in symmetric monopole scheme grounding the system neutral point among different options [9]. Xiamen Island project in China uses bipolar configuration with third cable return while Caprivi Link overhead line is a monopole system comprising ground electrodes. The solely hybrid installation joins Norway´s and Denmark´s electrical grids composed of two monopoles linked as bipolar transmission system. Skagerrak 3 pole is LCC-HVDC topology meanwhile Skagerrak 4 pole uses IGBT converters being only transmission line uses mass impregnated cable (MI) in VSC-HVDC system.

Another milestone of HVDC technology was completed in 2013 when first multi-terminal VSC (MTDC) project was commissioned in China. Nanao and Zhoushan MTDC projects consist in 3 and 5 terminal DC system respectively. Immature MTDC technology, high costs and the star-up/shutdown procedures lead to not to use circuit breakers in design. Additional information related to both projects is shown in [10-11] and TABLE II.

TABLE II.- VSC-HVDC multi-terminal projects in operation.

Project	Power (MW)	Converter topology	Voltage (kV)
Nanao	200/100/50	MMC	±160
Zhoushan	400/300/100/100/100	MMC	±200

According to European Commission established document "European Energy Security Strategy" previously mentioned, renewable and indigenous energy primary sources must be generated at least at 27% rate in 2030. On the other hand, security of supply should be guaranteed even knowing intermittence behaviour of solar, wind and hydro technologies. The integration of the European common electricity market by increasing the exchange of surplus green energy with HVDC links between neighbour countries makes prices go down for consumers [12]. Since the new European electricity grid expects diversified clean technologies and strengthen whole infrastructure, several VSC-HVDC new links are being developed for next years as TABLE III shows [6-8].

TABLE III.-VSC-HVDC links in development.

Project	Year	Power (MW)	Distance (km)	Voltage (kV)
SydVästlänken	2016	2x720	200	±300
Maritime Link	2017	500	187	±200
Caithness Moray Link	2018	1200	160	±320
NEMO Link	2019	1000	140	±400
COBRA Cable	2019	700	326	±320
Savoie-Piemont Project	2019	2x600	190	±320
New Jersey Energy Link	2019	3000	-	±320
Nord.link	2020	1400	623	±500
NSN Link	2021	1400	750	±515
Ultranet Project	2022	2000	340	-

B. Other applications

Other applications of the VSC-HVDC technology are the back-to-back converters and electrification of platforms oil / gas from the ground, although their use is currently limited when compared with conventional technology.

Back-to-back converters are mainly located between different region grids and interconnection is not needed.

The first area is located in the US, because its network is divided into 4 unsynchronized zones despite having the same frequency, coexisting with LCC-HVDC converters. Kriegers Flak Station consists on connection of Nordic and European regional grids between Denmark and Germany using VSC type back-to-back converter [7].

TABLE IV.-VSC-HVDC back-to-back converters.

Project	Year	Power (MW)	Voltage (kV)
Shin-Shinano III	1999	53	±10,6
Eagle Pass	2000	36	±15,9
Mackinac Station	2014	200	±71
Tres Amigas Station	2016	3x750	±326
Kriegers Flak Station	2019	400	±140

The second application area is located in Norwegian waters, where ABB developed a system of electrification of drilling platforms from the ground. The main goal of supplying electrical power from onshore to these offshore plants, consists in replacing gas or diesel generators and compressors by AC-DC-AC controlled system thus increasing the yield of the plant. Up to now, large amounts of greenhouse emissions were released to atmosphere due to great amounts of fuel consumption in diesel generators leading to cost raisings. In Table V VSC-HVDC commissioning and developing projects for oil/gas rigs are shown.

TABLE V.-VSC-HVDC links in oil/gas rigs.

Project	Year	Power (MW)	Distance (km)	Voltage (kV)
Troll A 1 & 2	2005	2x40	70	±60
Valhall	2010	78	292	-150
Troll A 3 & 4	2016	2x45	70	±60
Johan Sverdrup	2019	100	200	±80

3. Offshore wind farms with VSC-HVDC transmission

Since first offshore wind farms were put into operation in nineties several advances related with costs, efficiency and reliability have been achieved. Squirrel Cage Induction Generators (SCIGs) were widely used at fixed-speed before AC-AC converters connected to rotor circuit permitted an electronic control of wind energy conversion systems (WECs). First offshore wind farm (OWF) using Double Fed Induction Generator (DFIG) was inaugurated in December 2002, 160 MW Horn Revs 1. In 2008 first Permanent Magnet Synchronous Generators (PMSGs) were employed in Kemi Ajoksen 1&2 OWFs adding full-scale converter between generator and connection grid point. However, these pioneering OWFs designs were similar to onshore ones, no redundancy was took into account distributing all turbines in single series circuits.

Nevertheless, as the power capacity is increasing and turbines will be fitted far away from coast, some aspects have gained importance as maintenance, redundant level or grid codes´ requirements.

Taking into account European Union set up objectives, over last few years several large OWFs are being planned specially in North Sea and Baltic Sea. Thanks to suitable wind conditions, electronic devices development and low depth waters, some of these OWFs are being located far away from coast, even more than 200 km till onshore connection point. Capacitive performance of submarine cables causes transmission capacity/distance limits and higher electrical losses in HVAC links. On the other hand, if HVDC transmission system is used, weight and space limitations on offshore platforms don't permit large layouts being implemented, so VSC-HVDC converters are the most suitable solution for offshore transmission.

The integration of these OWFs into onshore grid can be divided into 3 electrical systems as can be noticed in Figure 1.

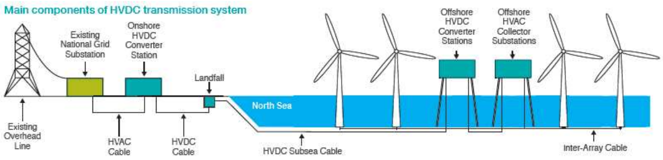


Fig. 1. Layout of overall OWF electrical system [13].

- Energy conversion system: turbines´ rated power has been increased and adapted for marine environment during the last years. Most recent tendencies show Direct Drive (or simplified gearboxes) PMSGs configuration is very attractive choice including full-scale converter in nacelle. According to TABLE VI VSC-HVDC links will support OWFs with PMSG turbines in 43,93 % and SCIG turbines will be employed in 40,61 % rate. It is obvious developers are paying attention to maintenance and problems related with slip rings because DFIGs are expected to be installed only at 15,46 %.

  These turbines are in the 3.6 to 8.0 MW range thought larger generators prototypes are being developed and tested at 10 MW range.

- Collector system: it comprises an AC offshore grid from medium voltage Gas Insulated Switchgear (GIS) placed at hub till offshore substation´s busbars. Turbines are set in 3 main different modes attending to offshore array network design typically 33 kV, although 66 kV voltage implementation is being considered in United Kingdom´s Round 3. Despite many researchers analysed different collector systems even in DC [14-16], in practice, developers are setting up low risk solutions as string, dentrite shaped and ring topologies, or combination of them. Energy produced by turbines is collected in AC platform where voltage is increased and sent to AC/DC converter station, wherever OWF developer must fulfil Grid Code´s requirements.

  Once MVAC is collected and increased by transformers in offshore substation to typically 155 kV (Germany) or 132 kV/220 kV (United Kingdom), HVAC export cable system transmits generated energy to AC/DC offshore converter.

- Transmission DC system: for large amounts of energy and long length submarine cables VSC-HVDC technology meet best technical and operational characteristics over HVAC option. Symmetrical monopole configuration is implemented in order to make it simpler layout.

A. Effect of redundancy in the design of OWF

During the last years redundancy is playing a key role in OWF systems when they are being designed. In energy conversion systems, currently, turbine manufactures connect in parallel modular sub-converters aiming for higher reliability in case of a device fail, it could result in stop of production.

On the other hand, developers are taking into account collector design topologies to achieve the best cost-reliability option.

Seven VSC-HVDC links are currently in operation in Germany, providing great amount of energy over long distances. Additional two links will be commissioned before 2020. Due to maintenance saving costs more than unique OWF share transmission link to shore, as can be noted in TABLE VI.

Among VSC-HVDC projects commissioned in Germany, BARD Offshore I wind farm is the only one which was designed in radial scheme by 8 cable feeders supporting 8 turbines each plus 4 strings connecting 4 turbines. Dentrite shaped option was adopted in Borkum Riffgrund I, Gode Wind I, and Gode Wind II OWFs in order to improve reliability.

By joining last turbines of two different strings with additional cable, new ring layout improves security in case of fault event in cable, GIS or connection point. This inter-link cable must be able to stand whole string power flow in the event of failure in cable next to the hub. Developer must decide level of redundancy in this case i.e. 50 %, 75 % or 100 % generally rated at average wind speed, according to dimensioned cross section cable. Trianel Windpark Borkum I, Nordsee One, Butendiek, Sandbank, Nordsee Ost, Meerwind Ost-Süd and Amrumbank West wind farms applied this topology. Global Tech I and Dan Tysk considered even further redundancy interconnecting combined rings and strings topologies in flexible way.

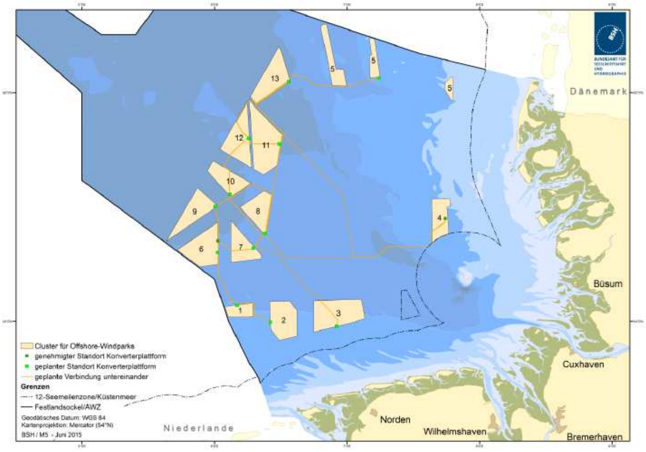
Regarding the transmission system, Germany and United Kingdom released both documents related with VSC-HVDC transmission security of supply. In Germany “Bundesnetzagentur für Elektrizität, Gas, Telekommunikation, Post und Eisenbahnen (BNetzA) published document Offshore-Netzentwicklungsplan 2013 (O-NEP) [18] explaining the main issues to fulfill by OFfshore Transmission Owners (OFTO). In United Kingdom, grid owner National Grid established conditions on security of supply by “Great Britain´s Security and Quality of Supply Standard” (SQSS) [19] document. Both publications ask not to lose more than 50 % of installed capacity of OWF in case of export cable fault or transformer damage. So, developers are obliged to install at least 2 export cables as well as 2 power transformers.

TABLE VI.-VSC-HVDC links commissioned before 2020 and connected offshore wind farms in Germany [17].

Link	Commissioning year	Power (MW)	DC link (km)	Converter topology	Voltage (kV)	Turbine	Offshore Wind Farm-(MW)
BorWin1	2010	400	203	2 level (OPWM)	±150	80xBard 5.0	Bard Offshore-(400)
DolWin1	2014	800	165	CTL	±320	78xSWT-4.0-120	Borkum Riffgrund I-(312)
						40xM5000-116	Trianel Borkum Phase I-(200)
						40xAD 5-135	Trianel Borkum Phase II-(200)
BorWin2	2013	800	200	MMC	±300	67xSWT-6.0-154	Veja Mate-(402)
						-	OWP Albatros-(400)
HelWin1	2013	576	130	MMC	±250	48xSE-6.2M-126	Nordsee Ost-(295,2)
						80xSWT-3.6-120	Meerwind Ost-Süd-(288)
SylWin1	2014	864	210	MMC	±320	80xSWT-3.6-120	Dan Tysk-(288)
						80xSWT-3.6-120	Butendiek-(288)
						80xSWT-3.6-120	Sandbank-(288)
HelWin2	2015	690	130	MMC	±320	80xSWT-3.6-120	Amrumbank West-(288)
DolWin2	2015	916	135	CTL	±320	55x SWT-6.0-154	Godewin1-(330)
						42x SWT-6.0-154	Godewin2-(252)
						54xSE-6.2M-126	Nordsee One-(332,1)
DolWin3	2017	900	162	MMC	±320	56xV164-8.0	Borkum Riffgrund II-(448)
						66xGE 6.0-150	Merkur OWF-(396)
BorWin3	2019	900	160	MMC	±320	80xM5000-116	Global Tech I-(400)
						71xSWT-7.0-154	EnBw Hohe See-(497)

In this context, in North Sea even further HVDC transmission system redundancy is being planned recently. North Sea Offshore Grid in Germany is considered bearing in mind an AC/DC converter or HVDC transmission cable system failures, providing a 100 % redundancy as Figure 2 shows [20]. The redundancy of the transmission system is achieved by means of the connection of clusters' converters. In fact, this could be the first HVDC multi-terminal grid in Europe.

Fig. 2. North Sea HVDC Grid plan.



4. Conclusions

Near future additional OWFs will be planned in Germany, Denmark, France, Great Britain, Belgium and The Netherlands, in HVAC or HVDC transmission mode. VSC-HVDC technology is also being considered in new emerging areas such Baltic Sea, China and east coast of USA.

When designing the OWF, three fundamental aspects must be taken into account: to fulfil grid codes, to reduce costs and improve the reliability. These aspects will determine the topology of the arrays of the WF, the number of transformers and substation technology as well as HVDC transmission.

This paper summarizes the current state of the design of OWF and introduces the future trends that will determine their evolution. The review presented in this paper is the basis for a new design methodology for OWF arrays being currently developed and tested with very promising results.

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