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Applications on power systems using HVDC-VSC technology

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Abstract.

This paper presents an analysis of the Voltage Source Converter-High Voltage Direct Current (VSC-HVDC) technology in power systems since it was implemented experimentally in the late nineties to the present. The main features as well as the main applications are explained attending to current projects in operation.

Additionally, a recopilation work has been made including two Annex. In the first one, all projects commissioned around the world have been summarised. The second Annex comprises multi-terminal projects in operation and planned during this decade.

Key words. VSC-HVDC, interconnectors, multi-terminal, back-to-back, hub, offshore wind farm

1. Introduction

Interconnections between neighbouring countries are of vital importance in the development of a common European grid since they allow the exchange of energy and the integration of renewable energies, thus facilitating the energy transition. It is also the starting point for the single European electricity market. In relation to this idea, in June 2019 the European Union (EU) established a minimum interconnection for member countries, indicating that the ratio between imported energy and installed generation power must be at least 15% by 2030 [1].

The main goal consists on eliminating any electrically isolated market and avoid restrictions for energy exchanges. There are also two additional conditions to this scenario: on the one hand, installed renewable energy generation follows an intermittent pattern that must be compensated with interconnections, and on the other hand, the electricity sector in Europe was liberalized in 1998, so the interconnections began to gain interest.

However, these interconnections require a series of conditions that from a technical and/or economic point of view cannot be met with High Voltage Alternating Current (HVAC) technology, especially those related to high power and long distances. For this reason, HVDC lines have responded to the new needs of the network, thanks to the development of power electronics and the cable industry. Thus, energy can flow freely between countries without any type of restriction, making the generation of electrical energy the most efficient in real time, the most competitive and from renewable sources.

Furthermore, HVDC lines have adapted very well to the requirements of the HVAC grid [2][3] and coexist properly. Hence, the first VSC-HVDC lines were commissioned in the late 1990s and subsequently, due to the importance that HVDC lines have gained, the EU adopted regulation 2016/1447 setting out the requirements to be met for grid connections via HVDC lines [4].

HVDC transmission is increasingly used worldwide for different reasons. One of them is that HVAC cables are affected by the capacitive effect, which limits the length that can be effectively used, especially in submarine or underground installations. There is the alternative of reactive power compensation to minimize this effect, but from a break-even point, the HVDC option is more effective despite the high fixed costs of converter substations.

2. Analysis of VSC-HVDC technology

As for VSC-HVDC converters, they use fully controlled electronic switching devices, usually Insulated Gate Bipolar Transistors (IGBTs), which allow higher switching frequency and better wave quality, as well as full control of the converter in terms of active and reactive powers independently managed [5].

In addition to the fact that VSC-HVDC technology's main utility is to transmit large amounts of electrical energy over long distances, several features make it very useful for other types of applications. The additional advantages of VSC-HVDC technology over HVAC and Current Source Converters (CSC-HVDC) technologies are very diverse and the following can be highlighted [6]-[11]:

- They have the capacity to control active and reactive powers independently because the converters can work in four quadrants. This means that these converters can absorb or supply reactive power on the HVAC side.
- Switch frequency can be smaller with low losses, currently about 1% per VSC converter or even lower.

- It allows changing the direction of the power flows quickly by maintaining the polarity of the voltage and reversing the direction of the current. In this way, it is not necessary to use any kind of switch or mechanical system to exchange polarities, making it ideal for multi-terminal networks.
- 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 CSC ones.
- It requires less conductors and insulators than HVAC for the same power to be transported, therefore it is cheaper and more reliable.
- For overhead installations the towers are simpler, cheaper and the width they occupy is smaller. This means that the costs for rights of way and the extension to occupy is lower, which can reach three times in the case of HVAC, which also produces a lower visual impact.
- For the same transmission power the line losses are lower and this is due to the Joule effect losses of the resistor and the absence of charge current. Because it loses less power and produces less voltage drop, it replaces HVAC technology which is no longer viable for high power and long distances. It also requires less wiring cross-section.
- Maintaining polarity is especially beneficial for XLPE cables since they are more prone to problems with polarity changes. In addition to being oil-free and therefore more environmentally friendly, they are lighter and less bulky. Their working temperature can reach up to 90°C
- They give the system greater flexibility to control power flows in multi-terminal networks.
- Transmission lines can be built in phases, starting with an asymmetrical monopolar line and converting it to bipolar in the future.
- It is possible to connect VSC-HVDC systems with capacitor or battery storage systems.
- They can feed passive networks or weak networks.
- They provide better response to network problems, help to regulate both voltage and frequency and service restoration (Black Start).
- They have the possibility of reconverting existing HVAC lines into HVDC lines in easy way.
- There are variants of submodules (Full Bridge), some of which have the ability to block DC faults, making it very interesting for overhead lines.
- The electromagnetic field is neutral around the cable.

These characteristics are specially interesting in such electrical areas working under different frequencies (Japan), non-synchronized regions (Europe, United States, China, Denmark), submarine lines, underground links or simply for exchange of great capacities of power. In [12] different electrical regions can be observed.

3. Applications of VSC-HVDC technology on the power system

As explained before, the number of projects using VSC-HVDC technology has been increased during last years. The applications are diverse thanks to the high flexibility level of this technology due to full control over switching devices. In Annex I and Annex II at the end of this paper, all projects commissioned are presented together with multi-terminal commissioned and planned projects. The applicatios are as follows:

A. Point-to-point interconnections

Point-to-Point interconnections marked the beginning of VSC-HVDC technology in the late 1990s, with 30 such interconnections currently in operation. These interconnections are especially useful when it is necessary to exchange the energy that a market/country produces in excess of its own demand, and consequently the generation system of the collective energy mix is used more efficiently because of this surplus. This situation contributes to the security of energy supply [13], diversifies generation sources by compensating for the intermittency and variability of renewable energy sources, as well as joining markets with different energy prices for the benefit of consumers. In this way, electricity markets that are more isolated could be the most benefited such as the United Kingdom with Ireland [14]-[16], the Iberian market [17][18], the Baltic countries and Italy [19].

The first projects were less than 100 km, for maximum power ratings of 60 MW, with ±80 kV voltage and underground XLPE cable. The objective of these pilot installations was to test and validate the operation of this technology on a small scale, to gain industry experience related to these VSC-HVDC links and to apply it to larger projects later on. These installations had two-level converters.

Improvements in IGBT technology as well as in IGBT control, converter and cable technology led to a rapid implementation of this technology in different types of interconnections. For example, the Tjaereborg and Nanhui onshore wind farm projects integrate the generation from two wind farms into the AC grid. It is worth highlighting the second phase of the Skagerrak project, which operates in a hybrid bipolar configuration, i.e. two poles operating independently in an asymmetrical monopolar configuration sharing both ends with different technologies. The Skagerrak 4 pole (VSC-HVDC technology) together with the Skagerrak 3 pole (CSC-HVDC technology) make up the hybrid bipolar installation. In this way, two typical problems of CSC-HVDC technology [20] can be minimized: (1) the reactive power control capability of the VSC pole allows reducing the dependence of the filters on AC, and (2) it allows compensating the reactive power thus stabilizing the voltage and reducing the risk of failures in the CSC switching.

Another type of working bipolar hybrid installation in China between the Baihetan hydroelectric power plant and the Jiangsu province, a distance of just over 2000 km, featuring converters of different technologies. The difference with respect to the previously mentioned case lies in the fact that the converters of different technologies are located at the ends of the lines, and the direction of the power generated does not change, the rectifier being a CSC-HVDC converter and the inverter end a VSC-HVDC converter. This type of hybrid installations are analyzed in [21]. Moreover, due to these enormous distances and the large capacity of this power plant, the solution adopted has been of extraordinary dimensions, implementing several ±800 kV transmission lines, the first with VSC-UHVDC technology. In addition, it has converters of different technologies where the transmitting end uses 8 GW thyristors and the receiving ends use IGBTs, with both Half-Bridge and Full-Bridge submodules [22][23].

B. Back-to-back stations

Another application of VSC-HVDC technology, consists in double converters settled into the same substation, also known as back-to-back converters. Although their use is currently scarce compared to the classic CSC-HVDC technology. This type of substations are located in areas where, from the electrical point of view, there are interconnected networks with different characteristics and they are not separated by any distance. These are areas where different frequencies coexist, have different non-synchronized networks despite having equal frequencies, or where networks are isolated from each other without additional transmission lines, making this option very interesting from a techno-economic point of view.

C. City center infeed

Large consumption centers, such as densely populated cities are experiencing a rapid growth in electricity demand. This means that the grids that feed these large cities are constantly being resized, to meet this increase in demand, so that the distribution networks suffer from bottlenecks, saturation and the risk of supply interruption at peak demand. On the other hand, space in city centers is very scarce and costly in case of upgrading the current networks, so a solution of small substations, easy installation of underground cables and flexible power control is necessary. Therefore, for the extension and development of networks within large urban centers, VSC-HVDC technology is the most suitable thanks to much smaller needed footprint.

D. Power from shore

Offshore oil and gas platforms are usually located far offshore. All of them use diesel-fueled generators to power the loads of these rigs or have HVAC lines from land to electrify them. For the companies that exploit these resources, it is especially important to eliminate diesel generators, since they emit polluting gases into the atmosphere, such as NO_x and carbon dioxide CO_2, which entail the payment of fees for their emissions, in addition to having a low efficiency. As a solution to avoid paying such fines, two different measures are being adopted: (1) installing offshore wind farms to electrically power the platforms or (2) electrifying them in a more flexible way from land with VSC-HVDC link to control the compressor motors by variable voltage/frequency, to extract the hydrocarbons and send them to the mainland.

E. Offshore wind integration

More and more countries are considering the implementation of offshore wind energy in their energy mix. The available offshore wind resource is far superior to onshore and more and more studies are being conducted to assess the potential of multiple sites. Therefore, this type of generation can be considered to be at an advanced stage of maturity, as demonstrated by the size of the wind farms that have been commissioned and their distance from the Point of Common Coupling (PCC). These distances and power ratings make classic HVAC technology not economically and technically viable, since the integration of offshore wind generation in HVAC is limited to approximately 80 km for a 400 MW farm at 220 kV, but thanks to the characteristics of VSC-HVDC technology, offshore wind has developed more rapidly.

F. Multi-terminal grids

One of the most interesting and promising applications of VSC-HVDC technology is to realize a multi-terminal network with at least three supply and consumption points, where a converter substation is installed and all of them connected by DC cables. These multi-terminal networks can be connected in three different topologies that have evolved from Point-to-Point interconnections: radial topology, ring topology and meshed topology with the possibility of interconnecting them both in symmetrical monopolar and bipolar configuration. The main features of these projects are shown in Annex II.

4. Results and conclusions of the study

This paper has analyzed VSC-HVDC technology and its applications in the power grid at present, as well as the commissioned projects and multi-terminal ones planned for this decade. All the main data collected in Annex I & Annex II have been summarized in Figure 1 (power rating), Figure 2 (voltage rating) and Figure 3 (current rating) respectively, showing how this technology is increasing year by year.

Due to the characteristics of the European grid, it is precisely in Europe where this technology is being implemented at a faster pace, since priority is given to the idea of having a flexible grid, covering different markets, different non-synchronized areas, integration of a large amount of renewable energy, with low losses at a competitive price.

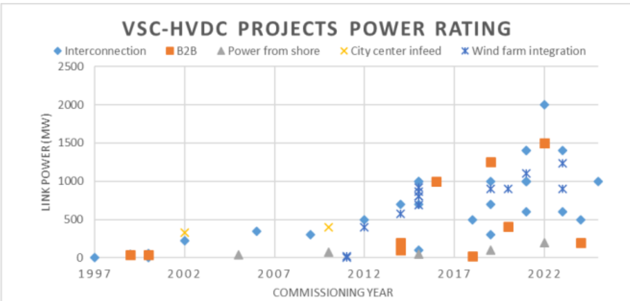

Fig. 1. VSC-HVDC projects by power rating. Own elaboration.

All these conditions have created the right situation for the implementation of this technology. Among the different applications described, it is worth highlighting the two that show the most promising future: multi-terminal interconnections and the integration of offshore wind farms.

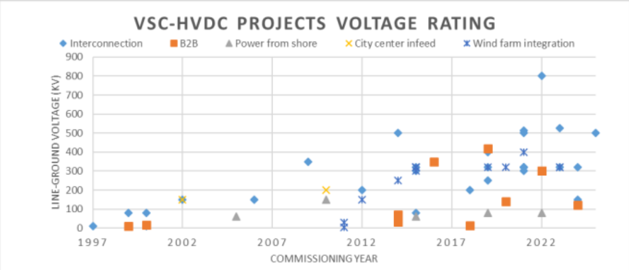

Fig. 2. VSC-HVDC projects by voltage rating. Own elaboration.

According to the characteristics of the projects under construction, the situation seems to indicate that they will continue to maintain this industrial standard until the end of this decade. However, there are reasons to believe that there will be changes after 2030 because the industry has basically opted for two innovations; (1) to develop another future option of ±525 kV for 2 GW of power to be transmitted per link in bipolar configuration with return cable to increase reliability, (2) to build substations on artificial/natural islands or large platforms, with the aim of integrating huge amounts of offshore wind energy to various markets. This would allow the lines between these hubs to play a dual interconnection-transmission role, making a multi-terminal grid more efficient, simpler and more economical.

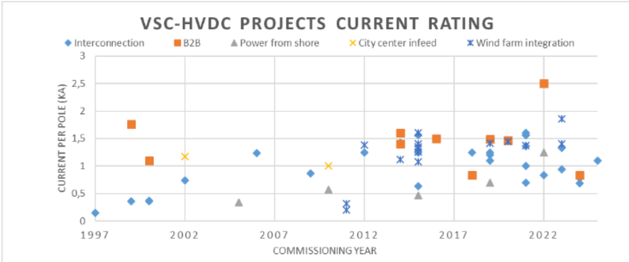

Fig. 3. VSC-HVDC projects by current rating. Own elaboration.

Annex I. – VSC-HVDC projects commissioned around the world [24]-[27].

Project	Country	Power (MW)	Voltage (±kV)	Current (kA/pole)	Distance (km)	System role	Year
Hällsjön	Sweden	3	10	0,150	10,2	Test	1997
Shin-Shinano 3	Japan	8x37,5	10,6	1,768	BtB	Frequency converter	1999
Gotland	Sweden	50	80	0,360	70	Interconnection	1999
Directlink	Australia	3x60	80	0,375	65	Interconnection	2000
Tjaereborg	Denmark	7,2	9	0,358	4,3	Test	2000
Eagle Pass	United States	36	15,9	1,100	BtB	Back-to-back	2000
Murraylink	Australia	220	150	0,739	180	Interconnection	2002
Cross Sound Cable	United States	330	150	1,175	40	City center infeed	2002
Troll A 1 & 2	Norway	2x40	60	0,337	70	Power from shore	2005
Estlink 1	Finland-Estonia	350	150	1,230	105	Interconnection	2006
Caprivi Link	Namibia	300	-350	0,867	950	Interconnection	2009
Valhall	Norway	78	-150	0,573	292	Power from shore	2010
Trans Bay Cable	United States	400	200	1,000	85	City center infeed	2010
Nanhui Wind Farm	China	18	30	0,315	8,4	Onshore wind farm	2011
WindFloat Prototype	Portugal	2	5	0,200	5	Test	2011
BorWin 1	Germany	400	150	1,382	200	Offshore wind farm	2012
East-West Link	Ireland-UK	500	200	1,250	262	Interconnection	2012
Skagerrak Pole 4	Denmark-Norway	700	+500	1,430	251	Interconnection	2014
Mackinac Station	United States	200	71	1,408	BtB	Back-to-back	2014
Mogocha Station	Russia	2x100	32	1,600	BtB	Back-to-back	2014
HelWin 1	Germany	576	250	1,120	130	Offshore wind farm	2014
SylWin 1	Germany	864	320	1,350	205	Offshore wind farm	2015
BorWin 2	Germany	800	300	1,320	200	Offshore wind farm	2015
DolWin 1	Germany	800	320	1,260	165	Offshore wind farm	2015
HelWin 2	Germany	690	320	1,080	130	Offshore wind farm	2015
Inelfe	France-Spain	2x1000	320	1,560	65	Interconnection	2015
DolWin 2	Germany	916	320	1,406	135	Offshore wind farm	2015
Xiamen Island	China	1000	320	1,600	10,7	Interconnection	2015
Finlandskabel	Finland	100	80	0,625	212	Interconnection	2015
NordBalt	Sweden-Lithuania	700	300	1,250	452	Interconnection	2015
Troll A 3 & 4	Norway	2x50	60	0,460	70	Power from shore	2015
Luxi Station	China	1000	350	1,500	BtB	Back-to-back	2016
Maritime Link	Canada	500	200	1,250	359	Interconnection	2018
Haengwon Station	South Korea	20	12	0,833	BtB	Test	2018
Johan Sverdrup 1	Norway	100	80	0,700	200	Power from shore	2019
NEMO Link	Belgium-UK	1000	400	1,250	142	Interconnection	2019
DolWin 3	Germany	900	320	1,410	162	Offshore wind farm	2019
Yu-E Station	China	4x1250	420	1,488	BtB	Back-to-back	2019
Cobra Cable	Netherlands-Denmark	700	320	1,093	325	Interconnection	2019

Hokkaido Pole 1	Japan	300	+250	1,200	122	Interconnection	2019
Kriegers Flak Station	Germany	410	140	1,464	BtB	Back-to-back	2020
BorWin 3	Germany	900	320	1,450	160	Offshore wind farm	2020
Nord Link	Germany-Norway	1400	500	0,700	623	Interconnection	2021
IFA 2	France-UK	1000	320	1,601	235	Interconnection	2021
Pugalur-Thrissur	India	2x1000	320	1,562	165	Interconnection	2021
ALEGrO	Germany-Belgium	1000	320	1,562	90	Interconnection	2021
NSN Link	Norway-UK	1400	515	1,359	750	Interconnection	2021
Eleclink	France-UK	1000	320	1,562	70	Interconnection	2021
Three Gorges Sea	China	1100	400	1,375	116	Offshore wind farm	2021
Sydlänken	Sweden	2x600	300	1,000	250	Interconnection	2021
Baihetan-Jiangsu	China	8000	800	0,833	2088	Bulk power link	2022
Johan Sverdrup 2	Norway	200	80	1,250	200	Power from shore	2022
Guangzhou Station	China	2x1500	300	2,500	BtB	Back-to-back	2022
Dongguan Station	China	2x1500	300	2,500	BtB	Back-to-back	2022
DolWin 6	Germany	900	320	1,406	90	Offshore wind farm	2023
Savoie Piedmont Link	France-Italy	2x600	320	0,937	190	Interconnection	2023
Viking Link	Denmark-UK	1400	525	1,333	767	Interconnection	2023
Dogger Bank A	UK	1235	320	1,860	224	Offshore wind farm	2023
Yangju Station	South Korea	200	120	0,833	BtB	Back-to-back	2024
Jeju Island 3	South Korea	200	150	0,687	100	Interconnection	2024
Greenlink	Ireland-UK	500	320	0,781	212	Interconnection	2024
Ariadne Link	Greece	1000	500	1,100	384	Interconnection	2025

Annex II. – VSC-HVDC multi-terminal projects commissioned & planned around the world [24]-[31].

Project	Links	Country	Power (MW)	Voltage (±kV)	Current (kA/pole)	Distance (km)	Year
Nanao	Sucheng-Jinniu	China	200	160	0,630	27,1	2013
	Jinniu-Qing´ao	China	100	160	0,315	12,5	2013
Zhoushan	Dinghai-Daishan	China	400	200	1,000	45	2014
	Daishan-Yangshan	China	200	200	0,500	39	2014
	Daishan-Qushan	China	100	200	0,250	17	2014
	Yangshan-Sijiao	China	100	200	0,250	32,3	2014
Caithness	Caithness-Moray	UK	1200	320	1,881	160	2019
	Caithness-Shetlands	UK	600	320	0,921	260	2024
Zhangbei	Beijing-Zhangbei	China	3000	500	3,000	219	2019
	Fengning-Beijing	China	1500	500	1,500	126	2019
	Zhangbei-Kangbao	China	1500	500	1,500	66	2019
	Kangbao-Fengning	China	1500	500	1,500	227	2019
WuDongDe	Yunnan-Guangxi	China	3000	800	1,875	905	2021
	Guangxi-Guangdong	China	5000	800	3,125	547	2021
Ultranet	North Korridor	Germany	2000	380	2,631	300	2027
	Süd Korridor	Germany	2000	380	2,631	342	2026
Heide Hub	LanWin 2	Germany	2000	525	1,904	250	2032
	LanWin 3	Germany	2000	525	1,904	211	2032
	NordOst Link	Germany	2000	525	1,904	165	2034
North West Hub	LanWin 5	Germany	2000	525	1,904	-	-
	NOR 20-1	Germany	2000	525	1,904	-	-
	Rhein Main DC 34	Germany	2000	525	1,904	523	2033
	Rhein Main DC 35	Germany	2000	525	1,904	461	2035
Tyrrhenian	East Link	Italy	1000	500	1,000	490	2025
	West Link	Italy	1000	500	1,000	-	2028
SACOI 3	Sardinia-Corsica	Italy	200	200	0,500	-	2029
	Corsica-Mainland	Italy	200	200	0,500	-	2029
Lion Link	Nederwiek 3-Mainland	The Netherlands	-	525	-	-	2032
	Nederwiek 3-UK	UK	-	525	-	-	2032
Nord Hub	NOR 12-3	Germany	2000	525	1,904	-	2033
	NOR 12-4	Germany	2000	525	1,904	320	2033
	NordOst Link Plus	Germany	2000	525	1,904	-	2035
EuroAfrica	Crete-Cyprus	Greece-Cyprus	1000	-	-	898	2029
	Cyprus-Egypt	Cyprus-Egypt	1000	-	-	498	2029
GiLA (Gascogne Sud)	Gascogne Sud-Loire	France	1200	320	-	-	2034
	Gascogne Sud-Gironde	France	1200	320	-	-	2034
GiLA (Olèron 2)	Oléron 2-Loire	France	1200	320	-	-	2033
	Oléron 2-Gironde	France	1200	320	-	-	2033

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