Paper presented at the IET International Conference on Frontier Computing, Hong Kong, November 18 - 21, 2012

The 9th IET International Conference, Hong Kong November 2012. Advances in Power System Control, Operation and Management.

HVDC Technology and Smart Grid.

Olaf Saksvik

ABBSweden

olaf.saksvik@se.abb.com

Abstract

Smart Grid is much more than IT and smart meters. A SmartGrid is an electricity network that can intelligently integrate the actions of all users connected to it – generators, consumers and those that do both – in order to efficiently deliver sustainable, economic and secure electricity. This article first gives a background to HVDC Transmission Technology in general, and secondly describes how HVDC Transmission Systems can be implemented in the network and used as backbones to establish strong and fully controllable transmission links, and thereby strengthening and increasing the reliability and availability of the electrical transmission system.

The article gives examples of how different types of HVDC transmission systems today is used to transmit large amounts of power over long distances, as interconnections between asynchronous ac networks including sea crossings, and for evacuation of large scale offshore wind-generated power.

Keywords: HVDC, Transmission Systems, Smart Grid.

1 Introduction

Utilizing HVDC links for long-distance transmission and for interconnecting HVAC grids is proven technology that has been in use for many years.

With the transition of power grids, based on sustainable generation, HVDC has become a key technology with several new applications. This includes connection of remote wind parks and strengthening of existing AC grids to cope with the introduction of renewable energy sources. In addition, traditional applications, such as bulk hydropower transfer and interconnections between regions, play a major role in our transition to sustainable generation and the associated grids.

With the increased number of applications, discussions are also underway to create DC grids, for increased flexibility and reliability. The technology for regional grids with a limited number of nodes is already in place and commercial projects have been commissioned (the Québec-New England project completed in the 1990s).

There are two fundamentally different technologies available for electrical power transmission: high voltage alternating current, HVAC, and high voltage direct current, HVDC.

HVAC has been the main technology used for power transmission for over a century, and it has served this purpose extremely well. However, for a number of technical and economic reasons, HVDC has inherent properties that make it much more suitable and convenient than HVAC for transmitting electrical power in certain applications.

This paper discusses applications for which HVDC is by far more suitable than HVAC for fulfilling specific requirements. This might be evacuation of power from offshore wind installations, remote hydro power generation, but also embedded in an AC grid where an HVDC link can add grid stability with controllable power flow and stable behavior under transient conditions in the grid.

2 HVDC Transmission Technology

2.1 A brief history of HVDC

HVDC technology is based on the use of high power electronics and advanced electronic control equipment. Research was underway as early as the 1930s and 1940s, and the first transmission link for commercial operation was commissioned in 1954. It was a submarine transmission link, feeding the island of Gotland, in the middle of the Baltic Sea, with power from the Swedish mainland. The Gotland transmission link has been upgraded a number of times and is still operational. The link is now used for ensuring stable power transfer to the island, and from the island to the mainland when there is a surplus of power produced by the island's numerous wind power units.

The Gotland submarine cable link was soon followed by a number of other transmission links using HVDC. The first major bulk transmission link using HVDC and overhead lines was the Pacific Intertie link, feeding the Greater Los Angeles area with bulk power from the hydropower stations on the Columbia River in the American Northwest. This was a record-breaking transmission link, covering 1,360 km and transmitting 1,440 MW. The Pacific Intertie link has been upgraded in several steps, and the present capacity is 3,100 MW.

The Itaipu transmission link in Brazil was by far the HVDC installation with the greatest capacity when commissioned during second half of the 1980s. It has a total rated power of 6,300 MW and at that time, world-record voltage of ±600 kV DC. The Itaipu HVDC link consists of two bipolar transmission lines, bringing power generated at 50 Hz in the Itaipu hydropower plant on the Parana River to the 60 Hz grid in São Paulo, in the industrial centre of Brazil.

The Xiangjiaba-Shanghai transmission link in China, commissioned in 2010, broke all the HVDC records in terms of rating. Using a record-high voltage of ±800 kV DC, it runs 2,071 km from the Xiangjiaba hydropower plant in southwestern China to the megacity of Shanghai. The power capacity is 6,400

MW, thus surpassing the rating of the Itaipu transmission link.

The longest HVDC transmission link planned thus far is the Rio Madeira-São Paolo link in Brazil, scheduled for completion in 2012. The distance covered will be over 2,500 km, and the operating voltage ±600 kV DC.

2.2 The basics of HVDC

HVDC links always require rectifiers/inverters to connect to AC grids. This is necessary for converting the alternating AC voltage to a constant DC voltage and back again. These rectifiers/inverters are referred to as converters in this paper.

The selection of HVDC over HVAC is typically motivated by the advantages provided by HVDC links:

- Considerably lower transmission losses compared to HVAC over long distances
- Enabling use of submarine cables over long distances and large amounts of power. A special case is the connection of remote offshore wind parks
- Enabling the use of underground cables over long distances and with high power
- Connection of asynchronous grids
- Full control of power flow, enabling efficient power trading between regions
- Added grid stability with controllable power flow and stable behavior under transient conditions in the AC grid
- Capability to recover from power failures utilizing adjacent grids, "black start"
- Small footprint for HVDC when overhead lines are used in comparison to corresponding AC overhead lines
- Magnetic fields from HVDC lines are negligible in comparison to corresponding magnetic fields for AC lines.

The trade-off is the cost of the HVDC converter stations and their footprints.

The advantages of HVAC transmission technology naturally assure that HVAC will continue to be the main technology of power transmission grids. However, due to the very nature and location of most renewable energy sources, HVAC is often impossible or too expensive to operate due to unacceptable transmission losses compared to the lower losses of HVDC.

In addition, HVDC is inherently more suitable for very large-scale and long-distance transmission than HVAC. This is because it requires a distinctly smaller footprint for transmission – either "invisible", with long underground or submarine cables, or with overhead lines requiring considerably less right-of-way compared to HVAC lines.

HVDC can be divided into two subcategories: LCC HVDC and VSC HVDC. The former is the "classic" HVDC technology, using power thyristors as the main components for converting AC to DC and vice versa. The present number of links based on this technology is exceeding 120.

VSC HVDC technology was developed during the 1990s, and the first commercial transmission link was commissioned in 1997, also on the Swedish island of Gotland in the Baltic Sea. VSC is based on power transistors, IGBTs (Insulated Gate Bipolar Transistors), as the converting components. IGBTs, being more controllable devices than thyristors, make VSC HVDC a more flexible and "intelligent" technology than LCC HVDC, and easily adaptable for transmissions from renewable and variable power sources such as wind farms. VSC HVDC technology is also suitable for building DC grids, interconnecting groups of wind farms or solar power installations for feeding mainland HVAC grids at various locations.

The two HVDC technologies are very similar, sharing the same knowledge base and basically the same auxiliary subsystems. To put it simply, VSC HVDC allows a flexible approach to geographically dispersed production systems and for grid building, while LCC HVDC has very high power transmission capacity, feeding power over vast distances, normally from large power generation plants to densely populated areas and industrial centers.

HVDC equipment and system know-how is commercially available from a number of manufacturers.

2.3 HVDC as a grid stabilizer

Contrary to the case with HVAC interconnections, HVDC power transfer can be controlled and measured precisely, greatly simplifying energy trading between different power grids and operators.

Due to the controllable AC output voltage and frequency of VSC HVDC links, they have the added benefit of increasing the power quality of the HVAC grids they are connected to. The result is increased grid stability, greater operating margins and a smoother AC voltage. The smoother AC voltage means lower flicker, which can be detrimental to lighting, particularly in industrial areas. Flicker also causes thermal losses in AC grids and in electrical and electronic equipment.

2.4 HVDC with overhead lines and cables

Both HVDC technologies are well suited for long cable transmissions where HVAC cannot be used. Long HVAC cables need extra compensation equipment due to charging of the cable system. This thereby considerably limits the use of HVAC for cable transmissions, especially at high power levels. Longer submarine and underground cables are thus only possible using HVDC.

For HVDC technology, whether LCC or VSC, there are no such technological limits, neither for the length of overhead lines or for submarine cables. Due to the capability of combining VSC technology and low-weight, extruded polymer insulated cables with their prefabricated joints; this technology is well suited for very long underground transmissions.

As a result, HVDC has been used for overhead transmission links exceeding 2,000 km and submarine cables up to 600 km, and with VSC technology, underground cables up to 180 km. These figures do not reflect the limitations of the technology, but rather represent the longest transmission distances operated or being built today.

Due to the somewhat different applications for the two different HVDC technologies, LCC is presently being used for transmissions using overhead lines and for submarine cables, while VSC is used for submarine cables, underground cables and to some extent for overhead lines. This does not reflect any limitations due to the respective technologies, but is instead a result of different market demands.

For high power HVAC transmission, three cables are needed, one for each phase. For high power HVDC transmission, only one pair of cables is needed – one with positive polarity and one with negative. In addition, HVDC cables have smaller diameter, lower weight and lower losses than HVAC of the same power transfer capacity [Ref. 1].

Cables used for VSC HVDC are strong, flexible and easy to install using the plowing technique. It is also possible to combine HVDC underground cables with overhead lines on the same link at locations where overhead lines would be more convenient.VSC HVDC cables utilize polymeric materials for insulation, which allows use of efficient production techniques and with environmentally sound materials.

Fig 1. Polymer insulated cables. Submarine cables in front and land cables at the rear

Fig 2. Cable laying in Australia

2.5 HVDC applications

Due to the reasons mentioned above, HVDC transmission technology plays a key role in the development of our future sustainable transmission grids. There are several important applications where HVDC has shown to be the most advantageous alternative in the grid toolbox. All of them assist in reducing CO_2 emission in different ways. The applications already delivered can be grouped as follows:

- Bulk power transmission from large, concentrated but remote energy sources, such as large-scale hydropower plants (LCC HVDC)
- Offshore wind farms and remote land-based wind farms, sometimes at a moderate distances from load centers but inaccessible to present HVAC grids (VSC HVDC)
- Embedded HVDC links for improving HVAC grid performance and that consequently facilitate introduction of renewable energy into the grid (VSC HVDC)
- National or regional grids that interconnect with one another (LCC and VSC HVDC)
- City Center Infeed. The growing need of power infeed into large metropolitan areas where the construction of new transmission due to right-of-way issues and tough requirements on compact space complicates traditional HVAC is an area which can be solved with HVDC and underground cables. (LCC and VSC HVDC).
- Supply of electrical power from shore to oil and gas offshore platforms (VSC HVDC)

2.5.1 Bulk power transmission

The great rivers originating on the Chinese and Indian slopes of the Himalayas, the Amazon River tributaries in Brazil and the Congo River in the Democratic Republic of Congo represent the greatest concentration of renewable hydropower resources on Earth.

The sites suitable for power stations are located thousands of kilometers away from populations and industrial centers. Power thus has to be transmitted point-to-point – from the power stations to load centers – in one leap, transmitting thousands of megawatts over distances varying from 1,000 km up to and above 2,500 km.

For transmission links of this size, more lines are needed for HVAC to transfer the same amount of power compared to HVDC, and reactive power compensation is needed. Furthermore, the HVAC overhead transmission lines require considerably wider right-of-ways.

With such extreme high-capacity transmission systems, LCC HVDC technology is necessary for reasons of economy and profitability.

A cost comparison between 600 kV DC, 800 kV DC and 800 kV AC over a distance of 2,500 km shows that the total costs – investments and line losses – are in the range of 25 percent lower for 800 kV DC than for 600 kV DC, which in turn has lower overall costs than 800 kV AC. [Ref. 2]

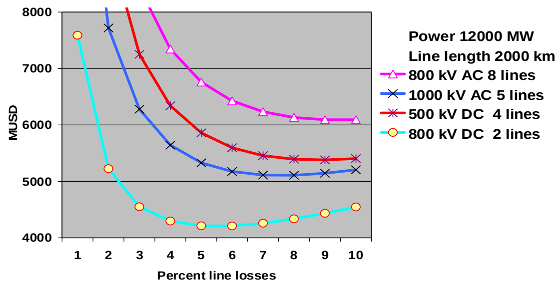

Fig 4. Cost comparison: 800 kV AC, 1,000 kV AC, 500 kV DC and 800 kV DC. [Ref 3].

The footprints in terms of right-of-way for the transmission lines are always considerably smaller for HVDC transmission than for HVAC. This can be of great importance closer to the receiving end of the line, in densely populated areas.

A 2,000 MW 800 kV AC transmission link require a right-of-way 75 meters wide, while a 3,000 MW, 500 kV DC transmission only require a 50-meter wide right-of-way. A 6,000 MW transmission link using 500 kV AC require seven power lines in parallel, compared to only one line when using 800 kV DC. [Ref. 3].

2.5.2 Offshore wind power

Transmission of power from large, offshore wind power farms is a challenge [Ref. 4, 5].

A remote wind power farm could be connected with either HVAC or HVDC. Depending on the size of the wind farm, along with grid conditions, the use of HVDC is applicable where the distance to the connecting AC grid exceeds 40-70 km.

When connecting a wind park to the main grid by means of a VSC transmission system, the wind park can easily be electrically separated from the main grid. This results in several technical and economical benefits for transmission system operators (TSOs), wind park developers and wind turbine generator manufacturers. Perhaps most importantly for TSOs is that a VSC-connected wind park becomes comparable to a normal power plant (although a generation with intermittent operation); the main grid-side of the VSC converter can be directly connected to a control or power dispatch center.

Another strong advantage is that AC faults appearing in a wind park or main grid will not be propagated by the VSC transmission system, which can provide benefits that include less mechanical stress on wind turbine generators. In addition, grid code compliance mainly becomes the responsibility of the HVDC converter supplier, resulting in simplification of wind turbine generators and consequently lowering associated costs. Furthermore, the inherent VSC voltage and frequency control capability simplifies wind park black starts and wind park energization transients will not transfer to the main grid [Ref. 6].

Offshore wind power farms are usually located on the continental shelves, far from coastlines. Prime examples are the large wind power farms planned for the North Sea and the Baltic. An existing example of VSC HVDC transmission from a wind farm is the BorWin1 project in the North Sea, off the German coast. The 400 MW Bard Offshore I wind park is connected to a 380 kV AC grid on the mainland via a ±150 kV VSC HVDC cable link, consisting of 125 km of submarine cables and 75 km of land cables.

Fig 6. Offshore converter station BorWin alpha offshore Germany evacuates wind-generated power.

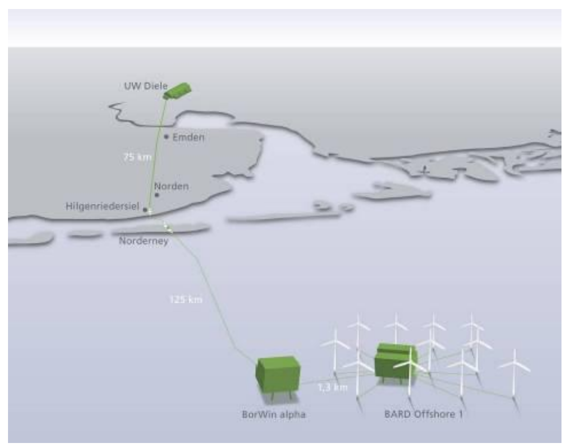

Fig 7. The wind park is situated 125 km from shore.

2.5.3 Embedded HVDC links

HVDC links have been used for many years to connect different grids, allowing controllable and precise power exchange between them. With VSC HVDC technology, this application can also be used for segmenting very large grids into smaller, more manageable and stable sub-grids. This segmentation can be an effective means for controlling and avoiding widespread disturbances and overcoming grid bottlenecks. Controllable and precise power flows also facilitate power trading.

Several studies show that VSC HVDC links within an HVAC grid can be successfully utilized for strengthening the entire transmission grid, especially under demanding load conditions and during system disturbances. [Ref. 7, 8, 9]

The typical reasons for employing embedded HVDC links are:

- Needs for removal of local bottlenecks in a AC grid
- Requirement for stabilization of an AC grid by means of the capability to add reactive power.
- Requirement for undergrounding due to visible impact of overhead lines in populated areas.
- Requirement for low magnetic field emissions in populated areas.

2.5.4 Interconnections

A traditional use of HVDC is the interconnection of systems in different countries and regions. This has been widely used to connect regions with different frequencies or when regions have the same frequency but they are not synchronized. It is also widely used when submarine cabling is required.

In recent years, with deregulation and the addition of more and more renewable energy sources, the number of built and planned HVDC interconnections has risen significantly. The increased installation of wind power, requiring back-up regulating power, also increases the demand for HVDC interconnections. for example, the NorNed link between the Netherlands and Norway. This link is used both to enable Netherlands to cover daytime peak loads, as well as to import backup power from “green” hydro-generated power from Norway. At night, the Netherlands normally export surplus thermally generated energy to Norway, which can “save” its water for the next day. The link is rated 700MW, at +/- 450 kV dc. The subsea cable has the world record length of 580 km, and the link has very low losses due to the high voltage (900 kV) across the converter bridge.

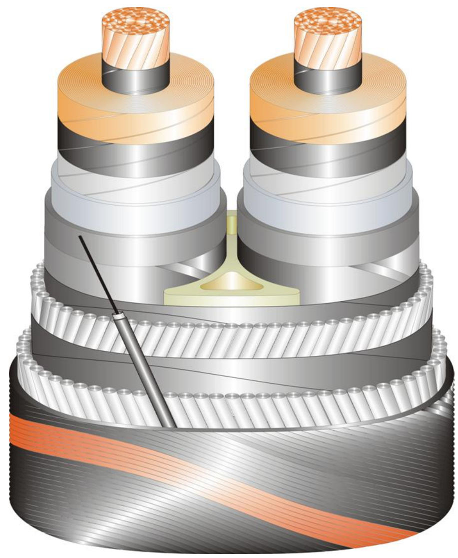

Fig 8. Double-armored +/- 450 kV submarine cable used for NorNed.

2.5.5 City Center Infeed.

As the size of a concentrated load in cities increases due to the on-going urbanization, metropolitan power networks have to be continuously upgraded to meet the demand. Environmental issues are also becoming more and more of a concern all over the world. Strong forces are pushing for replacing old local generation with power transmission from cleaner sources.

Land space being scarce and expensive, substantial difficulties arise whenever new right-of-way is to be secured for the feeding of additional power with traditional transmission lines. With increasing power levels, the risk of exceeding the short-circuit capability of existing switchgear equipment and other network components becomes another real threat to further expansion. Increasing demands on the power quality in urban areas is also a factor to consider for the power system engineer.

Therefore development of urban networks stands to address the issues of congestion, pollution, acoustical and electrical noise, short-circuit power restriction, permits and scarcity of land area for sites among others. Urban electrical power systems with steep demand increase need easily located solutions with short lead time from decision to in-service transmission. Even when AC cable solutions can offer sufficient power ratings, the problems of load controllability and short circuit power increase with every added circuit.

2.5.6 Supplying oil and gas offshore platforms with electrical power from shore

The HVDC power-from-shore application has been implemented in several projects. The motivation is to reduce costs for power generation offshore as well as to reduce CO_2 emissions. Power generated on shore typically produces much lower levels of CO_2.

One such project is power supply to the offshore platform Valhall, situated in the North Sea [Ref. 10].

Fig 9. The Valhall complex in the North Sea.

3 Conclusions

HVDC is an established technology that has been in use for more than 50 years. During the first 30 years, it was more of a niche technology, with a limited number of projects per year. With the changes in demands, and also due to evolving environmental needs, HVDC has become a common tool in the design and development of transmission grids. Key factors for this have been the recent developments within HVDC, with the step-up in voltage to 800 kV as well as the VSC technology. With these developments, remote sources of power can now be tapped that were previously inaccessible. This also applies to remote wind power and these developments will be essential in connecting the increasing number of offshore wind farms both in the North Sea region and elsewhere.

By using HVDC, transmission grids can be optimized and controlled to support the introduction of renewable generation into the grid. Finally, HVDC has also become useful in supplying power to offshore oil and gas installations.

All the listed HVDC applications in Chapter 2.5 in this document are helping to ensure the transformation of our energy systems for a sustainable future. HVDC transmission systems are at present being planned for, and materialized into projects, with a speed and volume by far exceeding what was expected and foreseen only a few years back. It is therefore safe to say that HVDC is playing a key role in the transformation of our energy systems.

4 References

1. *HVDC Light Cables for long distance grid connection*, Kenneth Johannesson, Anders Gustafsson, Johan Karlstrand, Marc Jeroense, European Offshore Wind Conference 2009
2. *Advantage of HVDC transmission at 800 kV*, Gunnar Asplund, Urban Åström and Dong Wu, Keynote Lecture, Beijing, China, August 25-28, 2005
3. *Bulk power transmission at extra high voltages, a comparison between transmission lines for HVDC at voltages above 600 kV DC and 800 kV AC*, Lars Weimers, CEPSI 2004
4. *Large scale offshore wind power energy evacuation by HVDC Light*, Peter Sandeberg, Lars Stendius, EWEC 2008.
5. *Challenges on the Road to an Offshore HVDC Grid*, Erik Koldby and Mats Hyttinen, Nordic Wind Power Conference 2009.
6. *HVDC with Voltage Source Converters – A Desirable Solution for Connecting Renewable Energies*, Ying Jiang-Häfner, Rolf Ottersten, Energynautics conference “Large-scale integration of wind power into power systems”, Bremen, Germany, 2009.
7. *AC grid with embedded VSC HVDC*, Jiuping Pan, Reynaldo Nuqui, Kailash Srivastava, Tomas Jonsson, Per Holmberg, Ying-Jiang Hafner, IEEE Energy 2030 Conference 2008.
8. *VSC HVDC control and applications in meshed AC networks*, Jiuping Pan, Reynaldo Nuqui, Le Tang and Per Holmberg, IEEE-PES General meeting, July 20-24, 2008, Pittsburgh, USA
9. *Power System Interconnections Using HVDC Links*, John Graham, Geir Biledt and Jan Johansson, IX SEPOPE Conference 2004.
10. *Valhall re-development project, Power from shore.* Hyttinen, Gilje, Westman. Cigre B4, Norway 2009.