HVDC – A key solution in future transmission systems

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Abstract

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). For more extensive grids, development and verification are ongoing in parallel to industry standards being discussed in various groups, such as ENTSO-E and CIGRE.

Résumé

L’utilisation de liaisons HTCC pour les transmissions à longue distance et pour l’interconnexion de réseaux HTCA est une technologie établie et utilisée depuis de nombreuses années.

Avec la transition des réseaux électriques, basée sur la génération d’énergie durable, HTCC est désormais une technologie clé, présentant un grand nombre de nouvelles applications. Cela inclut notamment la connexion de parcs éoliens distants et le renforcement du réseau en courant alternatif existant, afin de faire face à l’introduction des énergies renouvelables. En outre, les anciennes applications (telles que le transfert d’énergie hydraulique de masse et les interconnexions entre les régions) jouent un rôle majeur dans notre transition vers une génération d'énergie durable et le réseau qui y est associé.

Le nombre d’applications augmentant fortement, des discussions sont également en cours pour la création d’un réseau en courant continu. L’objectif est d’optimiser la flexibilité et la fiabilité.

La technologie impliquant des réseaux régionaux avec un nombre de nœuds limité est déjà utilisée, et des projets commerciaux sont déjà en place (le projet Québec-New England finalisé dans les années 1990). Pour les réseaux plus vastes, le développement et la vérification se fait maintenant et les standards industriels font l’objet de discussions dans des groupes différents comme ENTSO-E et CIGRE.

Keywords

DC grids, HVDC, renewables

1 Introduction

Harnessing rich and sustainable energy resources – such as wind power, solar power, and large-scale hydropower – is to a considerable extent, not a matter of generation technology but rather technology for electric transmission.

A large part of the renewable energy resources are located in remote areas – at sea, in unpopulated areas and in deserts. The optimum use of these resources, on a regional and global scale, often requires the construction of new power grids affecting several countries, regions and operators.

Consequently, in order to fully utilize the huge potential of sustainable energy sources, technically as well as economically, the choice of transmission technology is of decisive importance. Moreover, the profitability of harnessing these resources requires interregional and international agreements and standards. These may sometimes be new, but it will more likely suffice with new or modified routines for applying the existing standards and agreements to new situations.

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

HVAC has been the backbone of 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 convenient and efficient than HVAC for transmitting power from "new", remotely located renewable energy sources.

This paper discusses grid solutions offered by the commercially available HVDC power transmission technology. It outlines the different applications of HVDC that have proven to be key tools in the construction of new sustainable transmission grids. Furthermore, indications are provided of the capabilities of future DC grids.

2 A brief history of HVDC

HVDC technology is based on high power electronics and 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 both for power transfer from 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 longest power transmission link in the world currently in operation is the Inga-Kolwezi (formerly known as Inga-Shaba) overhead link in the Democratic Republic of the Congo, covering a distance of 1,700 km.

The Itaipu transmission link in Brazil is by far the HVDC installation with the greatest capacity. It has a total rated power of 6,300 MW and a soon to be broken, world-record voltage of ±600 kV DC. The Itaipu HVDC link consists of two HVDC 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 link was commissioned during the second half of the 1980s.

The Xiangjiaba-Shanghai transmission link in China, due to be commissioned in 2010, will break all the HVDC records. 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 will be 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.

2.1 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. These rectifiers/inverters are referred to as converters in this paper. For a DC transmission link, there is typically one converter at each end of the link.

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

- Low transmission losses over long distances
- Enabling submarine cables over long distances. 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 constitute the backbone 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 having smaller footprints than HVAC lines.

The most recent HVDC technology is also well suited for building sub-grids, collecting power from geographically dispersed renewable energy sources.

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 around 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 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 from large hydropower plants to population and industrial centers.

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

2.2 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.

2.3 DC overhead lines versus HVDC cables

Both HVDC technologies can be used 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 limits the use of HVAC cables to a maximum of around one hundred kilometers at high power levels. Longer submarine and underground cables are only possible using HVDC.

For HVDC technology, whether LCC or VSC, there are no such technological limits, neither for the length of overhead lines nor for submarine cables. Due to the capability of combining VSC technology and low-weight, extruded polymer insulated cables with their prefabricated joints, this technology can be used 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 HVDC, 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 a pair of cables is needed – one with positive polarity and one with negative. In addition, HVDC cables have smaller diameters, lower weights 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 use polymeric materials for insulation, materials which are not hazardous to the environment.

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

Fig 2. Cable laying in Australia

3 New infrastructures for renewable energy

The major resources of renewable energy are located either far from existing population and industrial centers, close to or even beyond the outer limits of existing HVAC grids, or fairly close to the load centers but inaccessible from the HVAC grids. The latter is the case with some of the large wind farms now being planned, especially along the coasts of Europe.

These renewable energy sources are also unevenly distributed on a global basis, requiring international cooperation and widely accepted agreements to be utilized to their full potential.

To be profitable, large-scale development of renewable energy production will require state-of-the-art HVDC technology. HVDC technology combines the flexibility, transmission capacity, controllability and operability required both by technical and commercial requirements.

3.1 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)
- Supply of electrical power from shore to oil and gas offshore platforms

In addition to the applications above, there is also the long-distance transmission of solar power from desert areas situated far from consumers. The HVDC technology for such an application already exists. However, as no such link has yet been constructed, it is not included in the discussion in this paper.

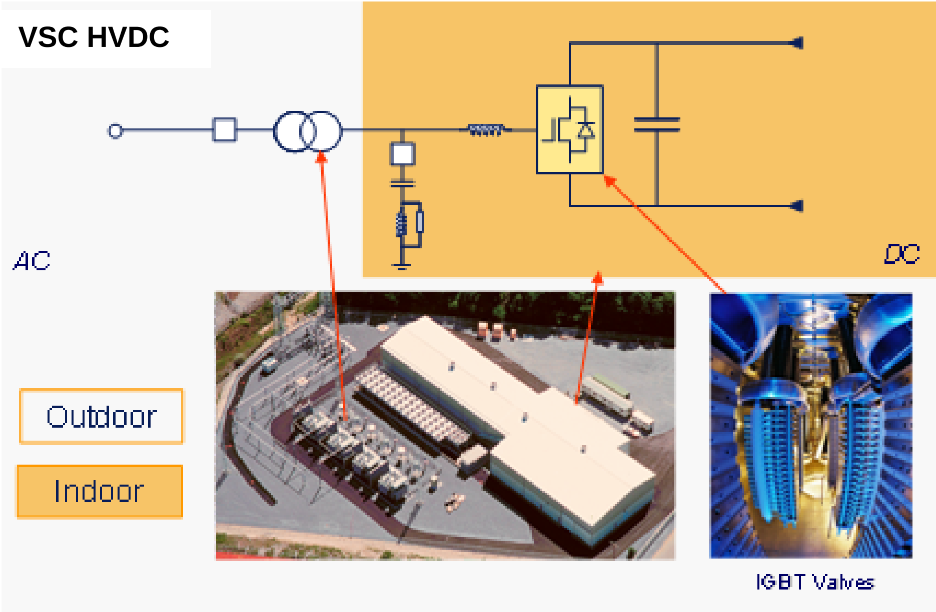

Fig 3. A VSC HVDC station has a small footprint.

3.1.1 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 population 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 2,500 km.

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

With such extreme high-capacity transmission, 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 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]

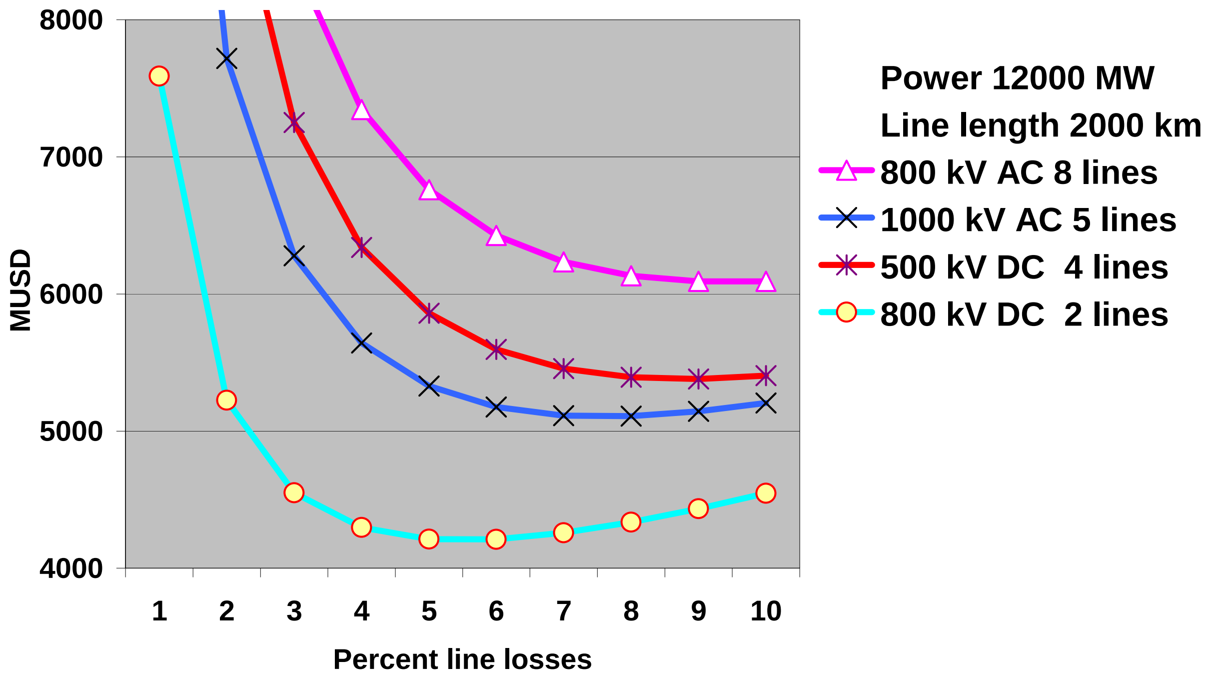

Fig 4. Cost comparison: 800 kV AC, 1,000 kV AC, 500 kV DC and 800 kV DC

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

A 2,000 MW 800 kV AC transmission link would need a right-of-way 75 meters wide, while a 3,000 MW, 500 kV DC transmission only would need a 50-meter wide right-of-way [Ref. 3].

A 6,000 MW transmission link using 500 kV AC would need seven power lines in parallel, compared to only one line when using 800 kV DC. In a 10,000 MW transmission system using 800 kV AC, the AC line would need five lines in parallel, whereas a 750 kV DC transmission would need only two lines in parallel. The corresponding width of the AC lines would be three times that of the DC lines [Ref. 3].

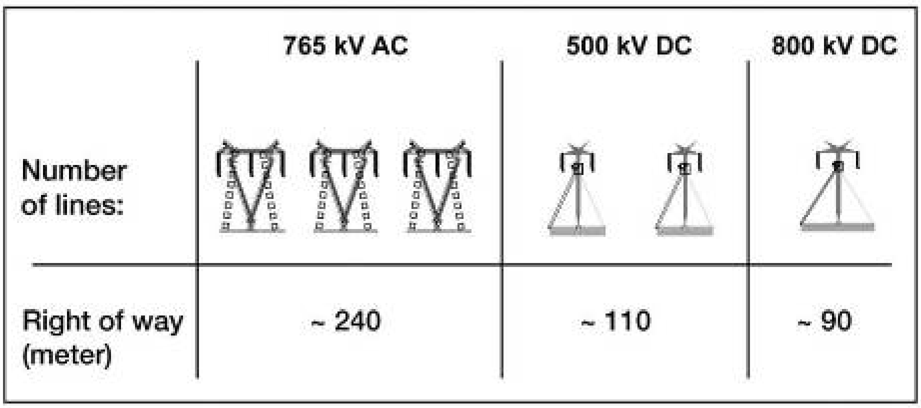

Fig 5. Example of right-of-way widths for overhead 6000 MW transmission lines

3.1.2 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 is disconnected 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 evacuates wind-generated power.

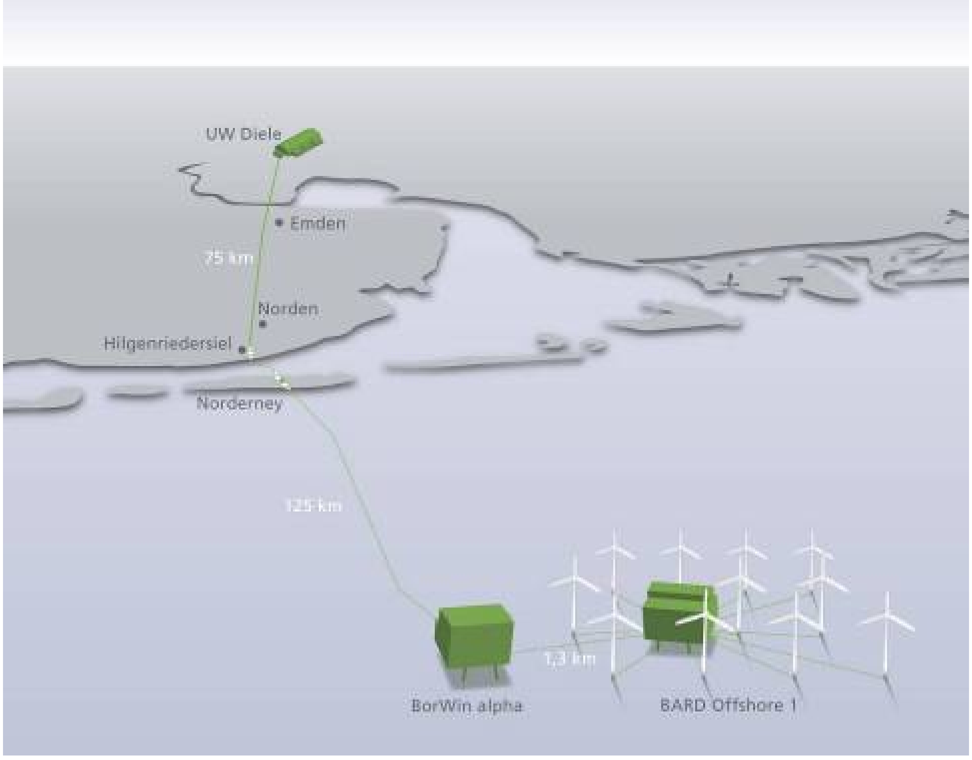

Fig 7. The wind park is situated 125 km from shore.

3.1.3 Embedded HVDC links improve HVAC grid performance

HVDC links have been used for many years to connect different grids, allowing controllable and precise power exchange between the grids. 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
- Requests for stabilization of an AC grid by means of the capability to add reactive power.
- Requests for undergrounding due to visible impact of overhead lines in populated areas.
- Requests for low magnetic field emissions in populated areas.

3.1.4 Interconnections

A traditional use of HVDC is the interconnection of systems in various 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 used when submarine cabling is requested.

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.

3.1.5 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 8. The Valhall complex in the North Sea

4 DC grids – Challenges and possibilities

DC links are today used for bringing offshore wind power to shore, supplying oil and gas offshore platforms, interconnecting power grids in different countries and reinforcing existing AC grids. With an increasing number of point-to-point DC connections, today connected through the AC grid, it becomes apparent that it would be beneficial to connect the DC links in a more direct manner. This takes us to the DC grids of the future.

Wider use of DC grids will definitely add several important features for handling future sustainable power generation, but it also involves challenges. To a limited extent, these are of a technical nature. The challenges mainly concern adaption of international regulations in order to manage such new grids.

4.1 Why an HVDC grid?

In connection with the future plans to introduce remote renewable power resources such as wind power in the North Sea, solar power in North Africa etc, the possibility for an HVDC grid has been discussed.

The value of an HVDC grid (offshore or on shore) is mainly in its role as a facilitator for power exchange and trade between regions and power systems. As such, it can introduce additional flexibility to power systems. Moreover, an offshore grid, as shown in Fig. 9 will allow the aggregation and dispatch of power from offshore wind farms from different regions, resulting in power generation profiles of low variability.

The major motivation for the offshore grid topology in Fig. 9 is constituted by two policy drivers: the need for connectivity between countries and power market regions, and the demand for economically efficient connection of offshore wind farms. While connectivity is considered the main driver at present, the connection of offshore wind farms will gain in importance in the future, when offshore converter stations for HVDC will be required for the connection of wind farms far from shore. The required converter stations will be on the open sea, and with additional investments, they will be able to be connected to each other or to another shore

This would allow for the allocation of the spare line capacity to the power market, when it is not used by wind power.

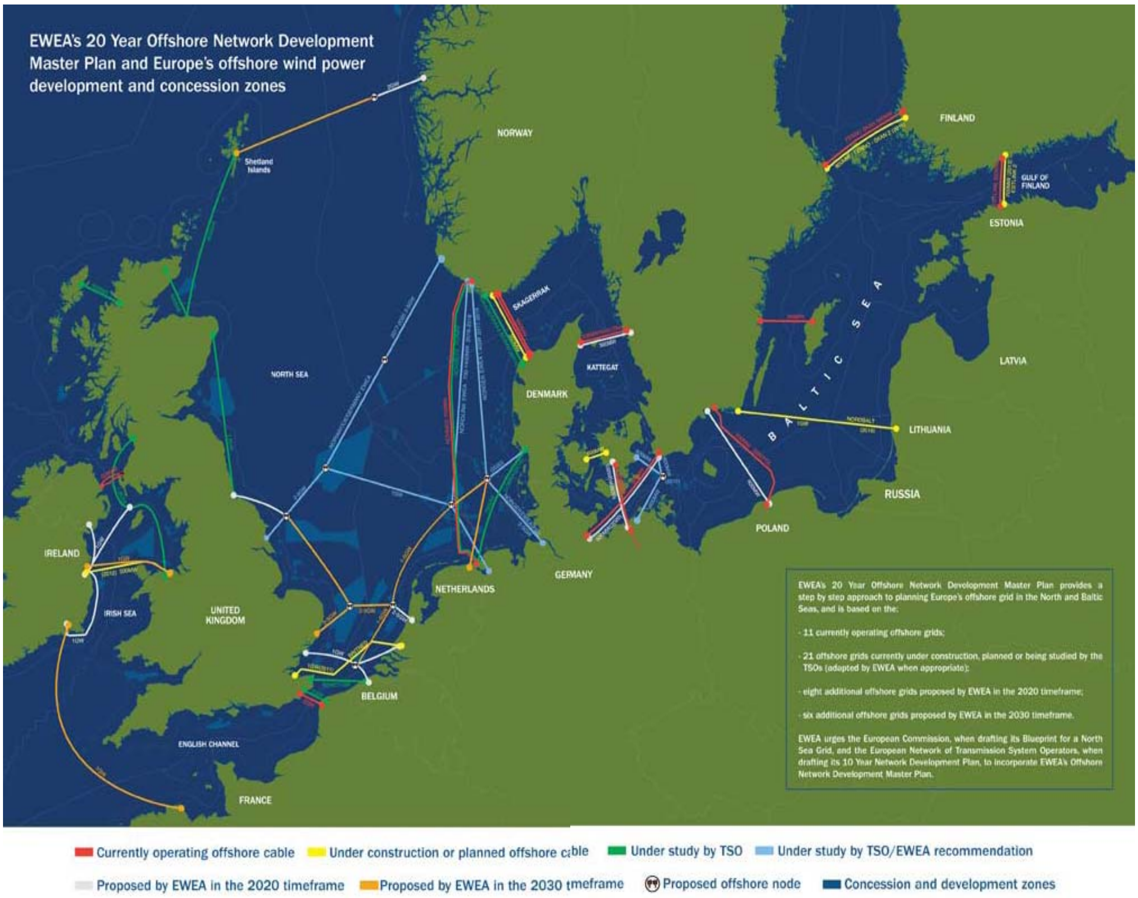

Fig 9. Offshore DC grid as proposed by EWEA (European Wind Energy Association) [Ref. 11].

The text in the lower left corner of Fig. 9 reads as follows:

"EWEA's 20 Year Offshore Network Development Master Plan provides a step by step approach to planning Europe's offshore grids in the North and Baltic Seas, and is based on the:

- 11 currently operating offshore grids
- 21 offshore grids currently under construction, planned or being studied by the TSO's (adapted by EWEA when appropriate)
- eight additional offshore grids proposed by EWEA in the 2020 timeframe
- six additional offshore grids proposed by EWEA in the 2030 timeframe

EWEA urges the European Commission, when drafting its Blueprint for a North Sea Grid, and the European Network of Transmission System Operators, when drafting its 10 year Network Development Plan, to incorporate EWEA's Offshore Network Development Master Plan.

4.2 Technical challenges of DC grids

A reference project for constructing a regional grid with a limited number of nodes is already in place. The Québec-New England project completed in the 1990s clearly demonstrates the feasibility of three-terminal HVDC systems [Ref. 12]. The new VSC technology will provide even better capabilities for operating regional multi-terminal systems.

When regional DC grids grow into meshed grids, there will be a need for control and protection schemes as well as for powerful breakers. The basic technologies in these fields are known although further development and verification is needed to fully meet all future needs and regulatory demands. .

4.2.1 HVDC standards for future HVDC grids

Standards will be called for in the future for harmonization of HVDC grids. A work group has been established within CIGRE, made up of both manufacturers and users [Ref. 13].

The work group is looking into reliability for DC grids and various grid configurations such as radial and meshed grids are reviewed. Because a grid has more branches than nodes, methodologies for power flow control are being investigated.

Based on the standard voltage levels used for AC grids, the work group will look into the recommend standard voltages for DC grids. The group will thus provide an important platform in engineering future DC grids.

4.3 Pan-European initiative in place to facilitate future grids

Future transmission grids will be more international, crossing economic zones and national borders, and will have to be operated and regulated by a mixture of international bodies as well as national agencies and system operators.

The establishment of the ENTSO-E (a European TSO cooperative association) in December 2008 was a major step towards future international cooperation and the formation of rules and frameworks to support future grids. A 10-year grid development program will be prepared every other year by all member TSOs to attain Pan-European optimization of grid expansion.

A corresponding Pan-European regulating agency will also be formed. This agency will be responsible for ensuring that the 10-year grid plans cover all necessary investments and for monitoring and evaluating implementation of these plans.

The formation of international bodies – regardless of whether the focus is on planning and investments as is the case with ENTSO-E or on technical harmonization as with CIGRE – they are building a solid foundation for future DC grids.

The international commitment to future DC grids was further supported in December 2009. During a European Union Energy Council meeting, ministers from UK, Germany, France, Belgium, the Netherlands, Luxembourg, Denmark, Sweden and Ireland signed an agreement – to develop an offshore grid in the North and Irish seas.

The proposed offshore grid will augment energy security for the participating countries while making it easier to optimize offshore wind power production. It will also assist the EU as a whole in meeting its renewable energy target for 2020.

5 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 due to evolving environmental needs, HVDC has become a common tool in the design of future global 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 hydropower 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 in the North Sea region.

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

DC grids will surely add several important features for handling future sustainable power generation, but it also involves challenges. There are technical challenges but the main concern is around international regulations in order to manage the grids of the future.

Most of the basic technology required is available and the fundamental standards are being developed.

All the listed HVDC applications in Chapter 3.1 in this document are helping to ensure the transformation of our energy systems for a sustainable future. HVDC systems ordered during 2007-2009 corresponded to connection of more than 30 GW of renewable energy. It is therefore safe to say that HVDC is playing a key role in the transformation of our energy systems.

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