SYSTEM APPROACH ON DESIGNING AN OFFSHORE WINDPOWER GRID CONNECTION

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Introduction

The deregulation of the electricity market has led to new challenges. In a competitive environment the rules for investment are influenced strongly by new types of generating facilities such as gas fired plants, wind farms and other renewables. Up to now almost all wind farms are located onshore. In Germany for example at the end of 2002 there were installed some 13500 windpower turbines with an installed power of more than 12 000 MW Because of the power values and trying to minimize investments this new type of generation normally enters the grid at sub-transmission levels. (≤ 110 kV).

Now sites suitable for additional wind farms onshore have become scarce in many European countries.. Therefore the major efforts today are directed to develop future wind farms offshore. In Denmark, UK and a few other countries the first offshore windfarms are already installed. Because of the size of the coming offshore wind farms it will be necessary to connect them to the high voltage level of the transmission system (in Europe normally at the 400 kV level).

A considerable part of planned offshore wind farms will be located far away from shore. Connecting them to the grid at the nearest possible point normally adds some more kilometers onshore to the distance of the wind farm to shore. Taking into account the main parameters power and transmission distance, the connection for an offshore wind farm needs to be optimized case by case.

These power transmission systems are normally comprised of a lot of submarine and land cables, AC switchgear, HVDC substations or AC compensation equipment, power transformers, OH lines, auxiliary equipment.

Sometimes discussion is ongoing regarding the application of VSC based technology or of conventional HVDC for the converters. For the latter type of converter also synchronous condensers may be needed offshore.

The total cost of the different solutions vary considerably depending on the chosen configuration. To reach the optimum solution of the power transmission a true system approach is necessary. This system approach requires a broad and at the same time detailed knowledge of the available main components and the capability to choose among them for the best suited devices with respect to the optimum overall function. So manufacturers in charge of a complete transmission system have a decisive advantage compared with those whose facilities cover only some individual components. This advantage becomes even more important, if the connections of several neighboring wind farms to the onshore grid are to be optimized.

Since repair of offshore equipment is long lasting and expensive and reduces the availability of the wind farm, it is important to design for adequate reliability. Thus the following aspects should be considered :

- use of components with a low failure rate
- redundancy to continue operation even at single component level failure
- provision for a short meantime to repair.

If a component is heavy or needs, after a major fault, to be shipped for repair to the factory, sufficient facilities and spare parts must be provided onboard the platform. This aspect determines to a great extent the design of the offshore station and platform. Therefore, a system approach in the early planning stage is needed, to provide acceptable availability and to avoid high costs at a later stage.

Support for the electrical power transmission grid

In order to understand the challenge of large offshore wind farms connected to the electrical power grid one has to be aware of how the grids are organized today and how they will probably be organized in the future.

Traditionally, the power transmission grid is designed as a vertically integrated system. The electrical power, at the place of generation transformed to high voltages, is transmitted over high voltage lines to the distribution systems and then to the loads. The European UCPTE power system is organized and operated country wise. Each country is responsible for the balance of its own production and consumption. In comparison to the total installed power relatively weak connections exist between the different national grids. These connections are mainly used for support in case of emergency. So the mean distances between generation and load are below or in the range of 100 km. The existing network in Europe is not designed to transmit bulk power over long distances. In the future with the infeed of some 10 000 MW installed offshore wind power transmission distances may probably reach 1000 km or more. This means that a new 400 kV infrastructure needs to be developed. Since HVDC transmission lines need less right-of-way than AC lines it is also possible that an overlaying HVDC grid will be developed and built as the most economic solution..

When the power arrives at a substation the voltage is transformed to a lower level and a sub-transmission system carries the power further to a distribution substation where the voltage again is transformed and electrical power is distributed to the consumers. This vertical system is well managed both with respect to investments and in the way it is controlled. Voltage and power flow is controlled by the use of the large generators since they are all equipped with voltage control facilities and power control. Further downstream the voltage is controlled by means of tap changers on the transformers.

Voltage control in a transmission system to a high degree is dependant on the production and consumption of reactive power. In a simplified way one can describe the transmission system as being mainly inductive and thus absorbing reactive power causing a voltage drop. Furthermore many loads are inductive, consuming reactive power, and thus further lowering the voltage. Without a proper voltage control the electrical power system will not function since all loads are designed to receive voltage within a specific range. This means that at the connecting point of large offshore wind farms with the main electrical grid the reactive power has to be balanced under normal operating conditions. In the past in the event of faults wind farms were disconnected immediately from the grid. Now, with wind farms growing into the range of big or medium sized power plants contribution to the short circuit fault current will be required from new wind farms. To support the system and in order to reestablish normal operation after faults in the power system as fast as possible the wind farms must remain connected to the grid as long as possible.

Main configurations for connections of offshore wind farms to the grid

Two alternatives are offered for connecting offshore wind farms to the main grid: AC and DC.

A major advantage of AC is the low station cost. However, with growing distance the cable cost become significant and above a certain distance prohibitive. Long AC cables produce large amounts of capacitive reactive power. The charging current of the cables reduces the transmission capacity more and more. The capacitive power of the cable needs to be balanced by inductive reactive power in order not to create problems with high voltages. Parameters to optimize an AC connection are the transmission voltage level and the number of cable systems to be applied.

AC connection means synchronous operation of the wind farm and the grid. All faults in the main grid directly affect the collecting AC grid offshore and vice versa . To mitigate this dynamic effect fast voltage control needs to be provided as is demonstrated below.

DC has the advantage of lower cost for cables and lower cable losses above a certain distance and thus compensates the high converter costs. So for longer distances DC becomes competitive for the investments as well as for the operating costs.

In addition the DC transmission generally decouples both grids, so that, for example, it allows asynchronous operation of the offshore wind farm AC network and the main grid. This facilitates, in case of faults in the network, a fast return to prefault power transmission. Using Voltage Source Converters (VSC) additional features are the possibility of island operation and black start. So DC offers more flexibility to support the main power system.

The system approach on designing a connection for an offshore wind power farm identifies among different configurations the most suitable and economical one.

The AC solution

Stationary voltage control using VAr compensators for wind farms

A major issue of AC connections is how to provide adequate reactive power control. For stationary operation mainly the symmetrical, relatively slow, reactive power control is important. The reactive power of the cables have to be compensated depending on the load. Maximum compensation is required at no load condition. During operation at rated power only about 50 to 60% of the no load compensation power is needed. The compensation equipment thus consists of two elements, one with fixed compensation and another with controlled compensation, both inductive. Fixed compensation requires less space than controlled compensation equipment and, therefore, is preferably placed offshore. Or in small unmanned stations behind the coast line. To maintain the voltage offshore within prescribed limits the voltage at the onshore end of the cable can be controlled. In addition the generators of the wind turbines can provide to some extent reactive power and voltage control.

Fig. 1 shows a typical configuration for an AC connection from an offshore wind farm to the main grid.

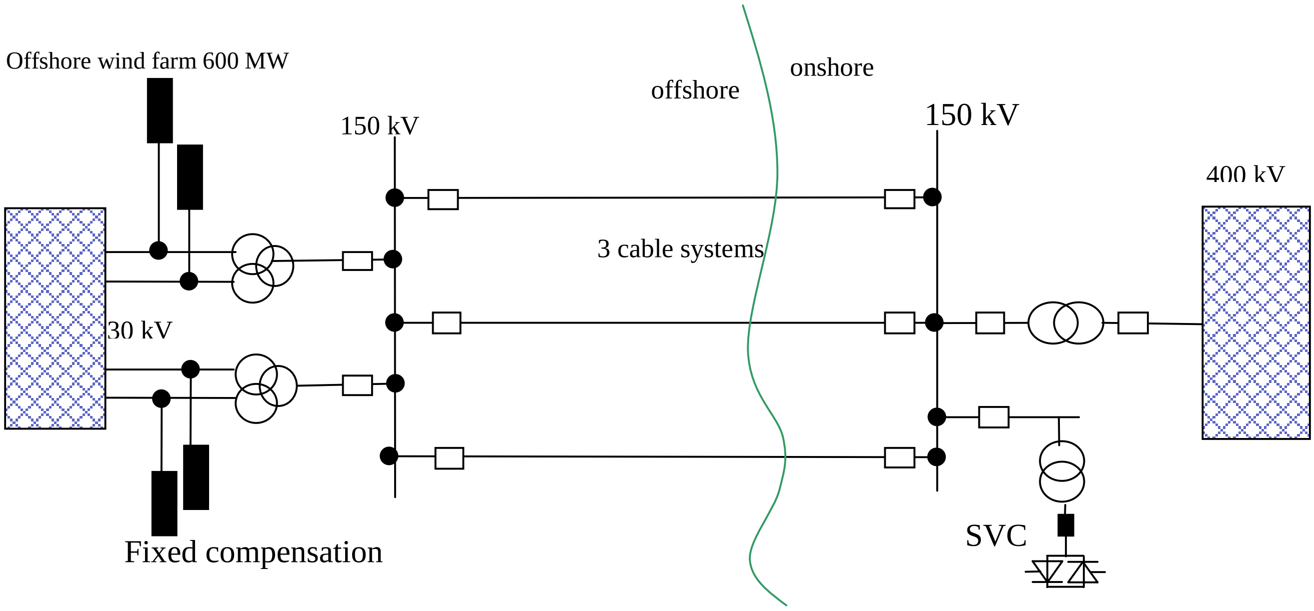
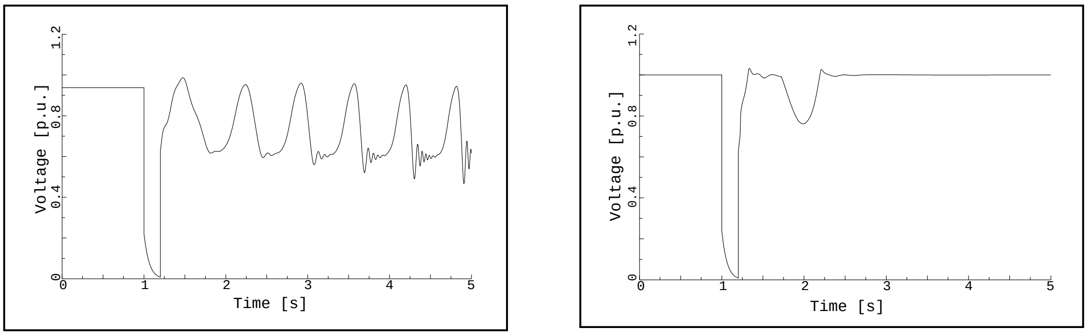


Figure 1. Principal configuration of an AC connection of a wind farm to the main grid

In the grid connection point a centralized approach using Static VAr Compensator (SVC) seems to be attractive. There the stationary production of reactive power provides the necessary balance of reactive power and controls the voltage in the grid connection point, making it possible to transmit the desired power levels. It is preferred to use some kind of regulating scheme continuously controlling the reactive power injection in the power grid as a function of the active power generated.

Dynamical issues

The reliable operation of power transmission systems depends to a high degree on the behavior of the connected loads and generators during and after faults have occurred in the grid. These faults are mainly temporary such as single line to ground faults caused by lightning. The faults are cleared by the protection schemes removing the affected line from the system. A typical case for existing wind farms would be a sub-transmission system feeding a substation close to the shore with existing outgoing lines from this substation serving small villages and industrial plants. A temporary fault on one of the outgoing lines will lower the system voltage. If the fault is close to the substation the voltage will immediately drop to almost zero. The system protection will identify the fault and the line will be disconnected and system voltage will try to recover. If recovery of the system voltage is successful or not depends to a certain degree on the loads and the dynamical support of reactive power, see figure 2 [1]. Typical loads being inductive and containing some induction motors will require large amounts of reactive power support to recover. When a new generating facility, such as a wind farm, is connected to the system it is extremely important to make sure the wind farm is designed to support the system during the fault. Depending on the type of wind turbine generators to be used, induction / double-fed / synchronous, the behavior during and after faults will be different, but all types need to be investigated carefully. The use of a centrally placed SVC improves the situation for all turbine types.



Without SVC

With SVC

Figure 2: Typical grid voltage behavior during and after a fault

Not only the almost instantaneously support of reactive power during and after fault, but also the possibilities of rapid control of the reactive power make SVC and wind farm a combination which will increase the prospects of AC connected wind farms becoming a new workhorse in the power generation business.

Beside the mentioned advantages the results of a real case study show what the system approach for an individual grid connection could mean:

Optimized design for combined connection of several wind farms

Two wind farms, „ A „ and „ B „ are planned nearby in the Baltic Sea west of the island Rügen (Fig. 3). Several configurations of grid connection were studied in detail, beside other it were the following:

1. separate AC connections to shore
2. combined AC connection to shore

As a result of the system optimization studies the following was found :

Variant	Main Component	Connection „ A „	Connection „ B „
1) separate connections	cables	2 cable systems 150 kV/ 200 MVA each / 110 km sea, 10 km land	1 cable system 110 kV/60 MVA, 50 km sea, 10 km land
	reactive power compensation	150 MVAr offshore, 150 MVAr onshore	30 MVAr onshore
2) combined connections	cables	2 cable systems 150 kV/200 MVA each 110 km sea, 10 km land	included in connection of „ A „
	reactive power compensation	75 MVAr offshore at „ A „, 150 MVAr onshore	+ 75 MVAr offshore at „ B „

Table 1. Two configurations for grid connections of the wind farms „ A „ and „ B „

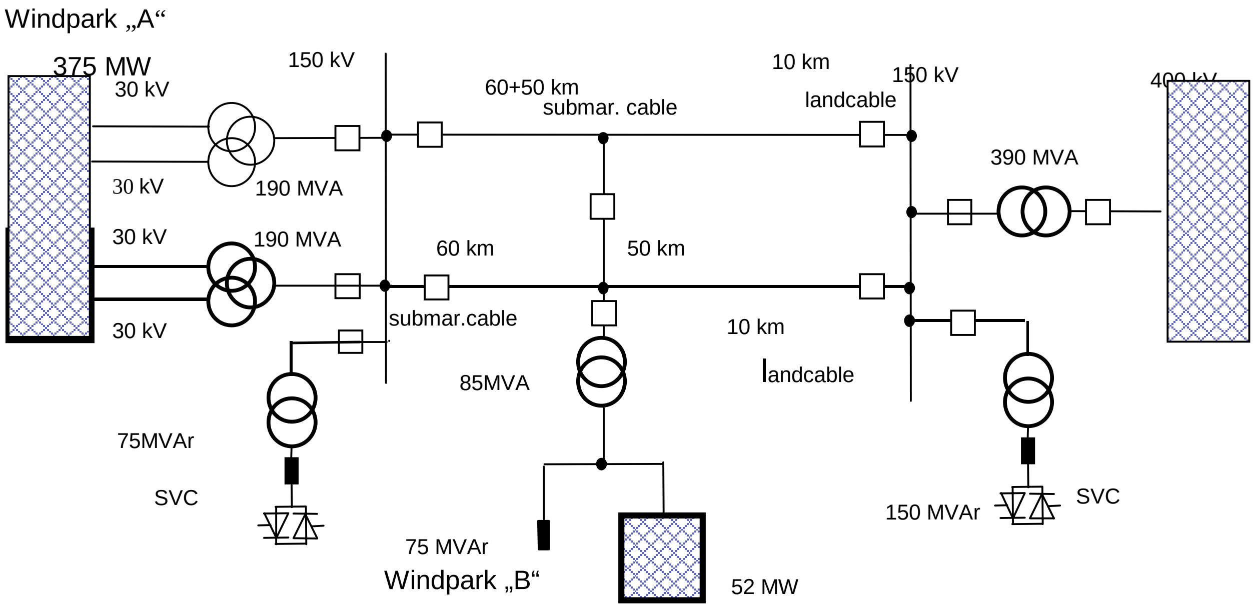


Figure 3. „ SLD optimized grid connection for Wind farms „ A „ and „ B

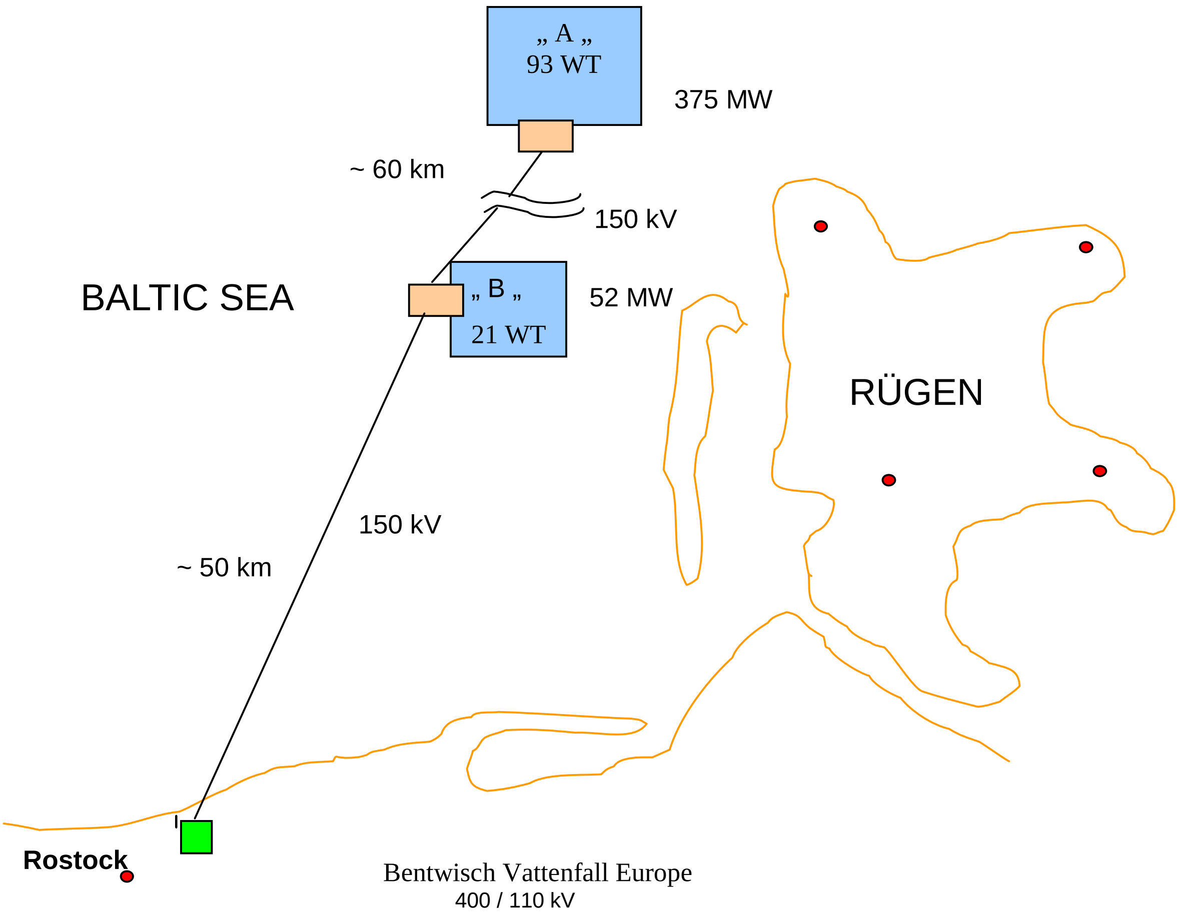


Figure 4. Wind farms „ A „ and „ B „ and their grid connections

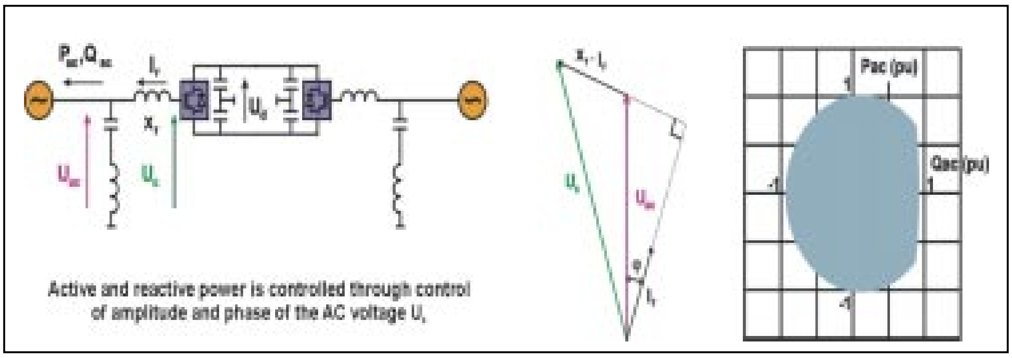
Table 1 summarizes the main technical data of the transmission cables for two possible solutions. Variant 2 with combined connection of the wind farms proves to be much more economic since the combined power of the two wind farms can be transmitted to shore with the same cable systems and the same total reactive power compensation as for the larger wind farm of both alone. The at the first glance surprising reason is the better use of the AC cables where the reactive power compensation can be applied more evenly along the length of the transmission, it can be interpreted as an addition of two shorter transmissions with compensation on both ends.

The DC solution

With wind power parks becoming a considerable share of the total power generation in a network, wind power will have to be as robust as conventional power plants and stay online at various contingencies in the AC network. As already shown, compensation will then be needed to preserve power quality and/or even the stability in the network.

HVDC Light is a DC transmission system based on **v**oltage **s**ource **c**onverter (VSC) technology which has characteristics suitable for connecting large amounts of wind power to networks, even at weak points in a network and without having to improve the short-circuit power ratio [4].

HVDC Light does not require any additional compensation, as this is inherent in the control of the converters (Fig. 5). From operation of installed systems experiences has been gained with HVDC Light transmission systems showing it as an excellent tool for bringing power from windmill parks to a network and at the same time contribute to AC voltage stabilization. An overview of a transmission system for bringing offshore wind power to a network with HVDC Light is shown in figure 6. An HVDC Light transmission system can control the active power transmission in an exact way, so that contracted power can be delivered when requested and when (of course) available from the wind situation. The power transmission can be combined with a frequency controller that varies the power to override or support the network frequency controller.



Active and reactive power is controlled through control of amplitude and phase of the AC voltage U_v

Figure 5. Active and reactive power control

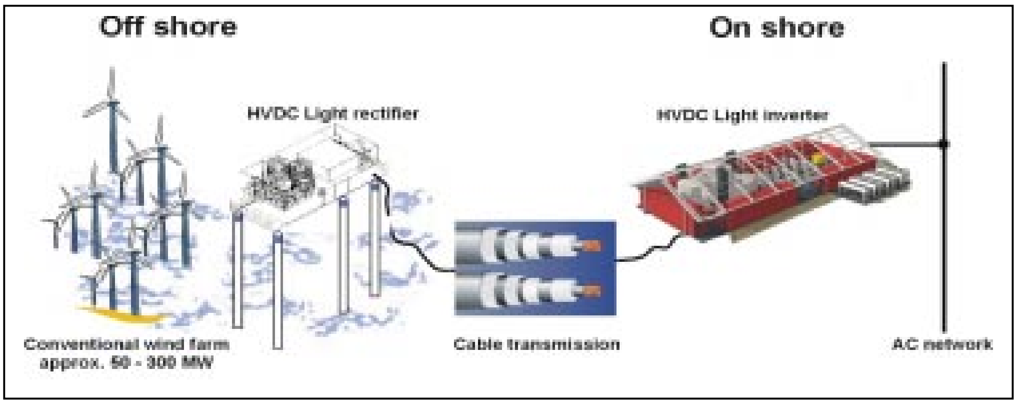


Figure 6. HVDC Light transmission system for offshore wind power

An HVDC Light converter controls reactive power for its AC bus and, in conjunction with a master controller, AC voltage control of the network connected to the converter station can be provided. Such AC voltage control can also be used to improve the power quality by including control of flicker and other transient disturbances.

In the case of connection to a passive network as for example a wind farm , the HVDC Light transmission system can provide control functions for active and reactive power, so that both voltage and frequency can be controlled from the converter station. In particular, this allows black starting by controlling the voltage and frequency from zero to nominal. HVDC Light connected to a wind farm could also give the possibility to provide reactive power to the windmills during the start up.

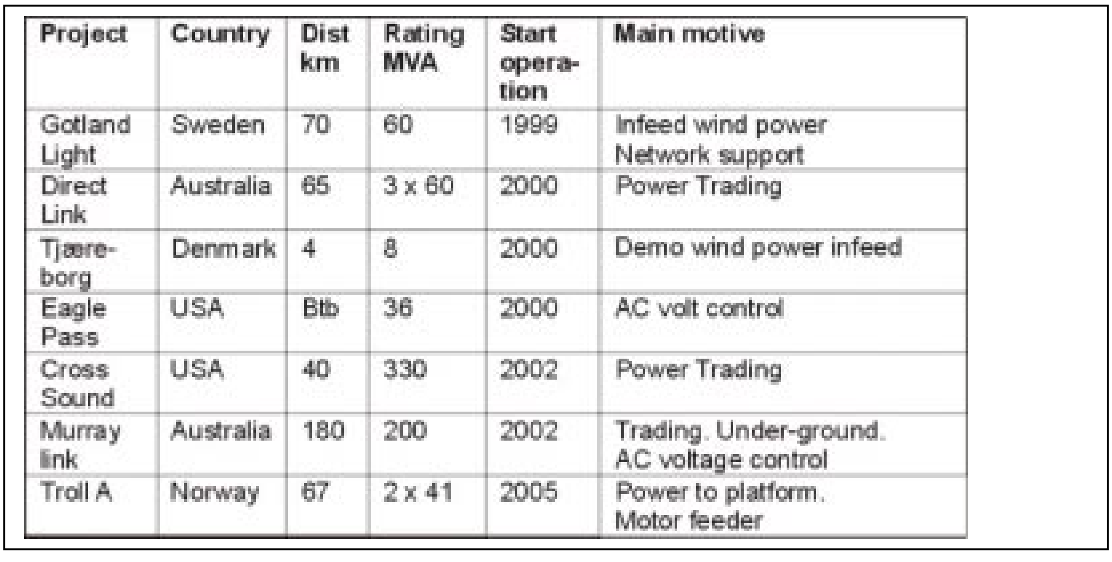
An HVDC Light transmission has only one significant value connecting both grids with each other: the real power in size and direction which is equivalent to the product U x I on the DC link. All the other physical values, which are typical for an AC grid (reactive power, apparent power, frequency, harmonics, DIPS, SAGS and flicker, etc.) are decoupled and do not affect the other grid.

Many of these values can be controlled and mitigated by intelligent control schemes from the converter feeding the respective grid.

Experience with HVDC Light installations

To date, six HVDC Light transmission systems have been contracted and put into operation. Another one is under construction to bring power from shore to the Troll A platform in the Norwegian part of the North Sea. These HVDC Light transmission systems are briefly presented in Table 2 below. They represent a variety of applications such as interconnection for trading, underground transmission for easy connection and transmission of wind power, power supply to platforms etc. In their operation they all take advantage of the comprehensive possibilities for control that a VSC converter offers.

Three of them have features that will be of special interest for power transmission from off-shore wind power generation plants and connection to a network. Gotland and Tjaereborg both connect wind power to a network and the Troll A has a converter designed for delivering power from shore to a platform in the sea.



Project	Country	Dist km	Rating MVA	Start operation	Main motive
Gotland Light	Sweden	70	60	1999	Infeed wind power Network support
Direct Link	Australia	65	3 x 60	2000	Power Trading
Tjære-borg	Denmark	4	8	2000	Demo wind power infeed
Eagle Pass	USA	Btb	36	2000	AC volt control
Cross Sound	USA	40	330	2002	Power Trading
Murray link	Australia	180	200	2002	Trading. Under-ground. AC voltage control
Troll A	Norway	67	2 x 41	2005	Power to platform. Motor feeder

Table 2. Existing HVDC Light transmission systems worldwide

The **Gotland** HVDC Light system rating is 50 MW and 65 MVA and it is connected in parallel with the existing 70 kV / 30 kV AC grid. The Gotland island system has a peak load of about 160 MW and today there are a total of 165 windmills with a total installed power of 90 MW producing about 200 GWh. The short circuit power from the AC grid is less than 60 MVA at the connection point in Näs, where the wind power production is connected for the HVDC Light system. The grid operator, Gotlands Energi AB (GEAB) considered, that HVDC Light would be the only realistic way to solve the technical problems with the high amount of wind power in-feed The experiences have supported expected improvements in characteristics such as:

- Flicker problems were eliminated with the installation of HVDC Light and transient phenomena disappeared.
- Stability in the system arose.
- Power flows, reactive power demands, as well as voltage levels in the system and harmonics were reduced.

One result is that the voltage stability during transient events has become much better with HVDC Light, which improves the output current stability from the asynchronous generators. This reduces not only the stresses on the AC grid but also on the mechanical construction of the windmills. Overall experiences are that the control of power flow from the converters makes the AC grid easier to supervise than a conventional AC network and the power variations do not stress the AC grid as much as in normal networks. Voltage quality has also been better with the increased wind power production [3].

The **Tjæreborg** wind farm consists of four wind turbines (WTs) with a total installed capacity of 6.5 MW and is a test installation. The DC pole cables have been installed in parallel with the existing AC cables, the sending end converter is installed at the wind farm, and the receiving end converter is installed in the Tjæreborg substation. The purpose was to investigate how the controllability of the VSC transmission as well as optimal exploitation of the wind energy by using the converter for providing a collective variable frequency to the WTs.

Simulation of three-phase faults demonstrated that the DC connection has the potential to improve wind farm performance during faults in the AC grid. The wind farm can be quickly isolated from the AC grid and rapidly recovers to full wind power production when the AC grid fault has been restored. It implies that the converters at both sides of the DC-transmission can stay in operation and connected to the grid, when a fault in the other grid occurs. Thus the requirement of shortest possible interruption in case of faults can optimally be obtained. Testing has shown that the converter station smoothly varies the frequency and that the frequency at the sending end can be controlled solely by the converter station, while the frequency in the receiving end is the AC grid frequency [4].

On the **Troll A** platform, two HVDC Light transmission system for 45 MW, +/-60 kV directly feed two high-voltage variable-speed synchronous machines designed for compressor drive with variable frequency and variable voltage with power from land [5]. On the platform equipment will be installed in housings that will be lifted on to the platform. Space and weight have to be kept to a minimum on an offshore installation. The HVDC Light concept therefore offers important advantages and thanks to smaller filters than conventional HVDC and no need for additional reactive power generation equipment it can be made compact and lightweight. The layout is kept compact on the platform by placing the converter equipment in a multi-storey module. The HVDC Light offshore converter is planned to be built as a prefabricated unit and transported and installed on top of the platform. The structure will have approximate main dimensions of W x L x H = 18 x 17 x 14 meters.

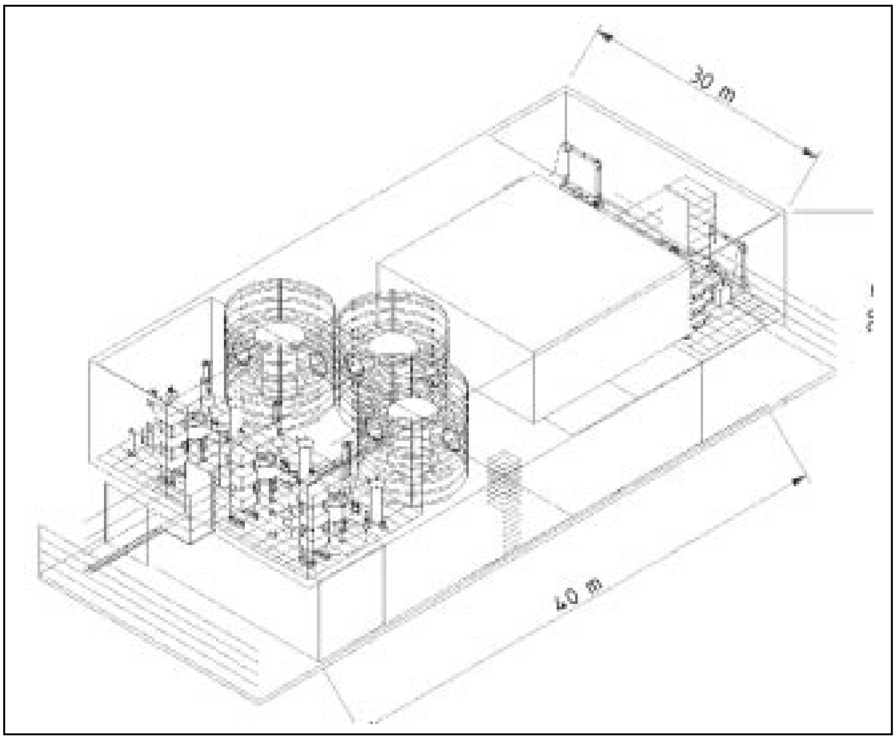


Figure 7. Multi-storey 350 MW converter designed for platform applications

For large wind farms an HVDC Light system of maximum rating, currently 350 MW, will probably be of more interest than the Troll A 45 MW units. A tentative design for such a converter in a three-storey enclosure has been made and would measure 30 x 40 x 20 metres. This would also include the transformer, which would be needed for connection to the windmills.

HVDC Light is a transmission system with direct current and thus has no technical limitations with regard to distance. This makes it the natural choice for long transmissions, when the distance becomes too long or uneconomic for AC transmission.

The operational characteristics of HVDC Light, which have been experienced in the operation, together with wind power as related above, makes it a strong alternative in many other situations, such as:

- infeed of wind power in points in the network, which are weak and/or causes problems with flicker, stability or other quality issues
- operation of the wind mill park at different and/or varying frequency, e.g. for optimum use of the wind energy

CONCLUSIONS

Vast experiences of both AC and DC transmissions show that both technologies are available and feasible for connection of large offshore wind power plants to a grid. A supplier with experiences from both technologies and having all components would be able to assist in the choice of transmission and connection system. All mentioned realized examples are projects resulting from feasibility and detailed studies of discussions, calculations and bench marks to find system optima in a long and trustful cooperation with customers and internal and external sub suppliers.

The results prove the quality of the system optimization process.

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