

HVDC Light Experiences applicable for power transmission from offshore wind power parks.

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ABSTRACT

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

HVDC Light is a transmission system that does not require any additional compensation, as this is inherent in the control of the converters. It will therefore be an excellent tool for bringing wind power into a network. To date, six HVDC Light transmission systems have been put into operation, of which two, Gotland Light and Tjaereborg are bringing wind power to networks. The experiences gained from the above installations of HVDC Light have shown that it is capable of handling wind power and of reacting rapidly enough to counteract voltage variations in an excellent way.

Another tendency today is to place large wind power farms offshore. An offshore wind farm isolated from the network by an HVDC Light transmission system would constitute a generation block, the operating frequency of which could be freely chosen. With the installation of HVDC Light converters on a North Sea platform, Troll A, experience has been gained of how to adapt converters for the rough environment of an offshore location.

1 INTRODUCTION

HVDC Light is a transmission system 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 ratio.

This is contrary to conventional AC transmission systems, which normally require a high SCR compared to the power to be entered [1]. This has been the measure that had to be taken to preserve the power quality in the network against the variations in voltage and power from the wind power. As long as the amount of wind power was small any quality problems this might have

caused were local. With big wind power parks coming along and becoming a considerable share of the total power generation in a network, wind power parks will have to be as robust as conventional power plants and stay online at various contingencies in the AC network. Various types of compensation will then be needed to preserve power quality and/or even the stability in the network.

HVDC Light does not require any additional compensation, as this is inherent in the control of the converters. It will therefore be an excellent tool for bringing wind power into a network. Experiences gained with HVDC Light transmission systems that are of importance for bringing power from offshore windmill parks will be presented in this paper, to show that HVDC Light is ready to go offshore.

2 WIND POWER, DEVELOPMENT OF HOW TO ENTER IT IN THE NETWORK

From the outset, opinions about wind power have been divided. From an environmental point of view it is wanted. It is seen as one way of reducing the emission of pollution, including carbon dioxide, into the atmosphere. From the power planning point of view it is difficult. The rapid variations in wind speed make it unreliable and impossible to schedule. The variations also contribute to voltage and frequency variations of more or less transient nature, thus affecting power quality. To preserve power quality, a high SCR compared to the power to be entered, will normally be required. As long as the amount of wind power was small this might only have caused local quality problems. Any wind turbine that causes a problem to the network could always be switched off if continued operation puts the wind turbine at risk.

With big clusters of windmills or wind power farms coming along, wind power is accounting for a considerable share of the total power generation in a network. Wind power parks will then need to be as robust as conventional power plants and stay online at various contingencies in the AC network [1]. Various types of compensation will be necessary to preserve the power quality and/or even the stability of the network. For conventional AC transmission from wind power farms, the connection point may be chosen differently than for conventional generation and/or requires an improved

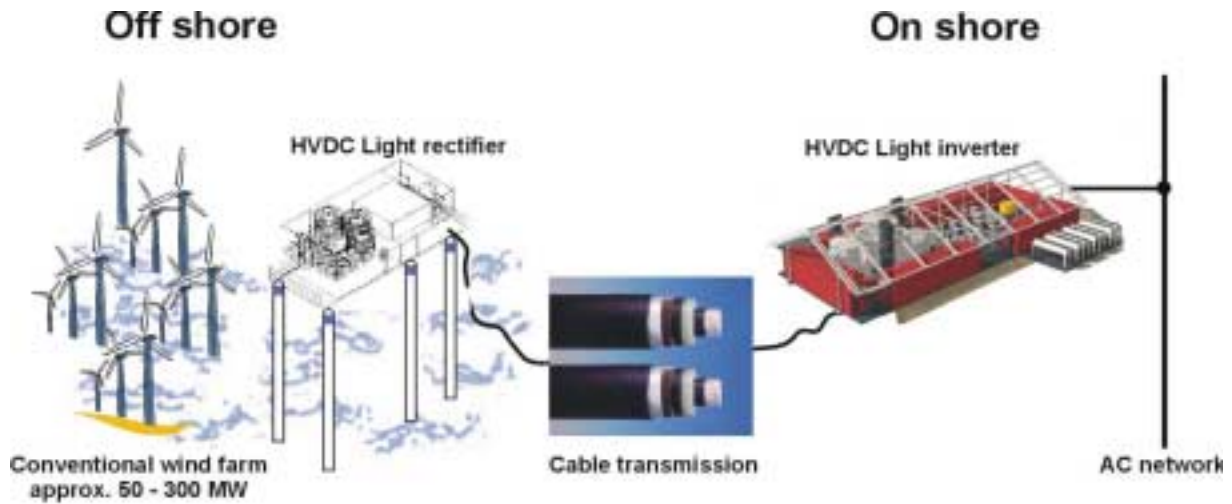


Figure 1. HVDC Light transmission system for offshore wind power

SCR. HVDC Light is a direct-current transmission system that does not require any additional compensation, as this is inherent in the control of the converters. It is therefore an excellent tool for bringing wind power into a network.

3 HVDC LIGHT CHARACTERISTICS

There are two basic components in an HVDC Light transmission system, an extruded cable and a VSC converter. Compared to other cable types, extruded cable is light, mechanically flexible and robust and can be designed for submarine, underground or aerial installation. The VSC converter is highly controllable of both active and reactive power. Today they exist for power levels up to around 350 MW with the semiconductor valves in modular movable housings. [2]

The use of components with a high switching frequency, such as IGBTs, allows pulse width modulation (PWM) to be used. This makes it possible to create any phase angle or amplitude (within limits) by changing the PWM pattern, which can be done almost instantaneously. With PWM, both active and reactive power can be controlled independently in this way.

An HVDC Light transmission system can control the active power transmission in an exact way, so that contracted power can be delivered when requested. The power transmission can be combined with a frequency controller that varies the power to override or support the network frequency controller.

An HVDC Light converter controls reactive power of the 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 power quality by including control of flicker and other transient disturbances.

In the case of connection to a passive network, 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 such a passive network will give the same control possibilities as the connection of a generator. The use of black start capability has been tested and/or foreseen in some cases.

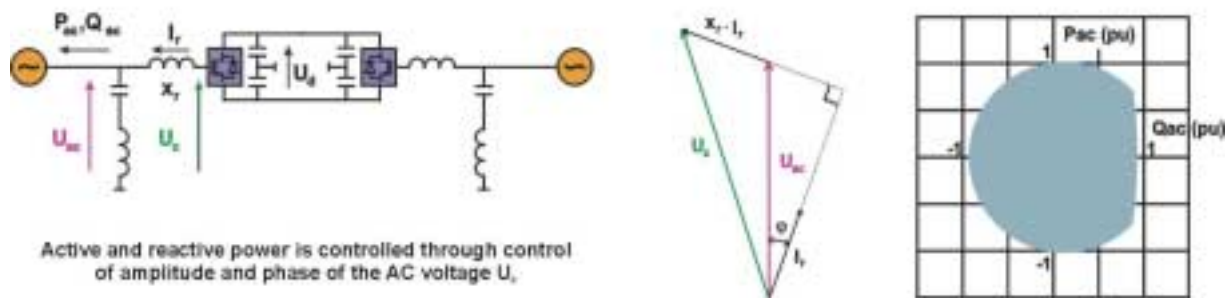


Figure 2. Active and reactive power control

4 HVDC LIGHT TRANSMISSION SYSTEMS IN OPERATION AND CONSTRUCTION

To date, six HVDC Light transmission systems have been contracted and put into operation. [2,3,4,6]. Another one is under construction to bring power from shore to the Troll A platform in the North Sea.

The HVDC Light transmission systems in operation and under construction are briefly presented in the table below. These installations represent a variety of applica-

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
Tjæreborg	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

tions such as interconnection for trading, underground transmission for easy permitting, 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 offshore wind power generation plants and connection to a network. Gotland and Tjæreborg both connect wind power to a network and the Troll A has a converter designed for operation on a platform in the sea. Next we shall see what experiences have been gained from these installations and to what extent they are applicable for a transmission of power from offshore wind farms.

5 APPLICABLE EXPERIENCES FROM THE GOTLAND HVDC LIGHT SYSTEM

The background to the building and installation of the Gotland HVDC Light system was complex: The existing wind power system had shown stability and voltage

quality problems. It was also supposed to meet the expected increase of the new wind power from the producers and to keep the power quality at the same level as before wind power was first introduced.

For the grid operator, Gotlands Energi AB (GEAB) the alternatives were to refuse all new wind power production on the grid or try to solve the technical problems. HVDC Light was considered the only realistic way to solve the technical problems [3].

5.1 Description of the Gotland electrical system.

The energy turnover in the system is about 850 GWh, the peak load is about 160 MW and the minimum load is about 40 MW. It is a meshed 70 kV system with some radial 30 kV lines and in addition there is the distribution grid. Most of the loads are located close to the connection point of the existing HVDC link from the mainland in the north part of the island of Gotland. This HVDC link normally supplies power from the mainland and regulates the frequency on the island. This makes the system very dynamic with low inertia. In such a dynamic system it is very important to have fast voltage control to avoid voltage collapse.

Today, in 2003, there are 165 windmills with total installed power of 90 MW producing about 200 GWh, which is double what it was when the decision to build the HVDC Light system was taken in 1997. In the southern part close to the southern station, Näs, 45 MW of wind power are installed. The AC line has a maximum thermal capacity of 18 MW.

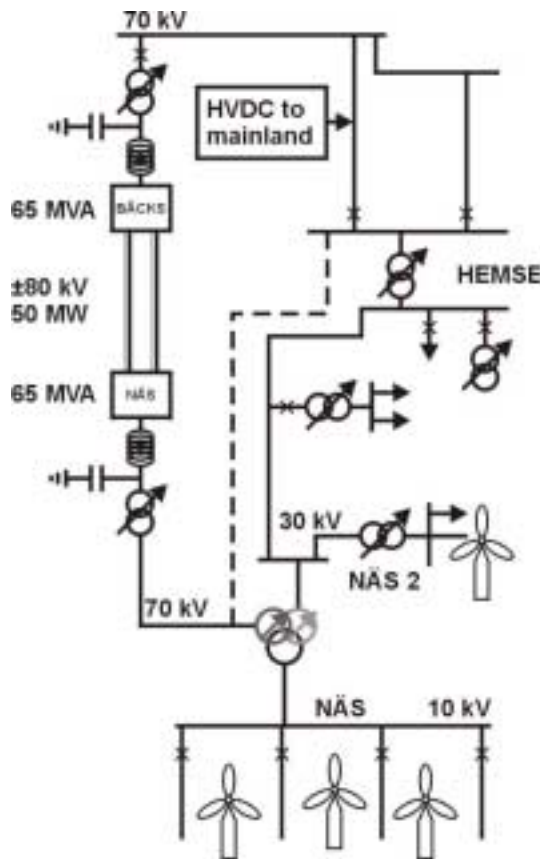


Figure 3. Simplified diagram of the Gotland network

The HVDC Light system is connected in parallel with the existing 70 kV / 30 kV AC grid. The short-circuit power from the AC grid at the connection point in Näs is less than 60 MVA. At this point the wind power production is connected for the HVDC Light system to transmit the power to the north. The rated power of the HVDC Light system is 50 MW and 65 MVA.

5.2 Grid technical aspects

For a successful expansion of the wind power, the electric system must be adjusted to be able to regulate and keep an acceptable voltage quality. For the present and increasing expansion of wind power production, GEAB has to ensure a secure supply with good voltage quality. The work on the inclusion of HVDC Light has raised new thinking on how to look at network issues such as short-circuit currents, flicker and power flows. One result is that the outputs of asynchronous generators are dependent on the voltage during voltage dips. If the voltage can be stable even during transient events, the output current from the generators will become more stable. This reduces the stresses on the AC grid but also on the mechanical construction of the windmills. This knowledge has been used to adjust the selectivity plans for relay protection with and without HVDC Light. It

has been possible to develop and implement such practical measures mainly thanks to the flexibility of HVDC Light.

The essential aspects to consider are:

- Flicker problems were eliminated with the installation of HVDC Light. Apparently the transient voltage control prevents locking to the flicker.
- Transient phenomena at which faults have been dominating.
- Stability in the system.
- Power flows, reactive power demands, as well as voltage levels in the system.
- Harmonics

5.2.1 Transient phenomena

The most significant problem has been transient phenomena during faults in the AC grid [7]. The parallel connection of HVDC with the AC grid and the weak grid in one station make the response time very important. Even the asynchronous generator behaviour has an impact during AC faults. It has been shown that a standard voltage controller cannot be used to manage these situations. The parameter settings have to consider that the system must not be too fast in normal operation and that it has to act rapidly when something happens. As there are no physical technical limits on the control possibilities of HVDC Light, this control situation has been solved by using special software algorithms to handle transient disturbances.

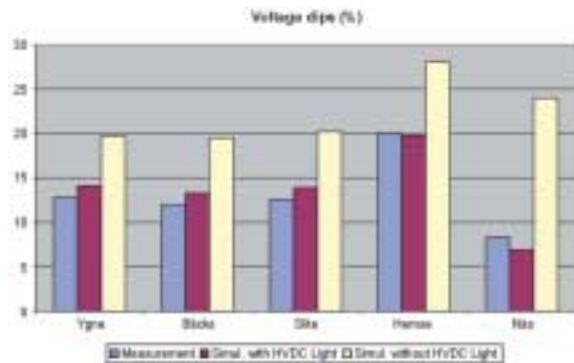


Figure 4. Voltage dips with and without HVDC Light

Studies of fault events have shown that the selectivity plans for protection must be redesigned where a large amount of wind power production is connected to a network. The behaviour of the asynchronous generators of the windmills is dependent on the voltage during an AC fault nearby the windmills. This is specifically important during recovery from the fault. If the voltage dip was deep, the current might be very high when the voltage recovers. This is a problem in conventional networks and will be considerably mitigated by HVDC Light's voltage control function.

One case of an AC fault was tested and is compared with the simulations on a system computer model with and without HVDC Light; see Figure 4. The fault, which is a real three-phase fault, was initiated at Garda, close to Hemse; see Figure 3. It was created by closing a 10 kV breaker to simulate a solid three-phase short circuit. When we did that, the voltage was measured at ten different locations.

The fault sequence was simple: to close the breaker and let the over-current protection trip the breaker again. The fault duration was no longer than 50 ms, but it showed the response from various equipment. The power responses from some windmills, the synchronous generators, the HVDC link and, of course, from HVDC Light, were measured. The results were compared with simulations under the same circumstances with and without HVDC Light.

5.2.2 Power flows

To meet the output power variation from the windmills, an automatic power flow control has been developed to minimise the losses and avoid overload on the AC lines. This is designed to work without communication with the despatch centre. During normal conditions the overall SCADA system determines the set points for active and reactive power to minimise the total losses in the whole system. This function is important so that there is no need for the operators to be on line and carry out the control manually. The same function will also avoid unnecessary tap changer movements. Previous experiences with conventional AC solutions from the time before the HVDC Light project had shown that manual control of this function is a problem .

If, for some reason, the HVDC Light system trips, the control automatically disconnects, within 100 ms, the amount of wind power production that was being transmitted on HVDC Light, plus a margin. This has to be done to avoid overload on the AC grid during disturbances on the HVDC Light system.

5.3 Operating experiences

The plant has been in continuous operation since February 2000 and the allowed wind power production has depended on the availability of HVDC Light. There have been some disturbances on HVDC Light, mostly due to teething troubles in the control system. Most of the problems have been solved and nowadays the plant can operate for months without any alarms at all.

We are still working to achieve improvements and to have even more safe operation during transient events. The issue is to get faster limitations for the current in the converter in order to avoid temporary blocking of

HVDC Light and AC protections. Some development engineering is going on to reduce losses in the system, and this is planned to be implemented during 2004.

Tests have been done to validate computer models for the HVDC Light plant and the whole system. HVDC Light has been used to introduce small signal disturbances to validate the wind power park responses. This was done simply for testing and research into the impact of wind power parks on an electrical grid.

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 been better even with the increased wind power production. The sensitive customers, such as big industrial companies, suffer less now from disturbances due to the voltage dips and other voltage quality imperfections. Even if the network cannot manage all AC faults, the average behaviour over a year points to much better voltage quality.

6 PRACTICAL EXPERIENCES FROM THE TJAEREBORG

The background to the Tjæreborg project was the plan to build and connect two 160 MW offshore wind farms to Eltra's transmission grid. The first 160 MW offshore wind farm at Horns Rev in the North Sea was put into operation in 2002. For this site, an AC cable connection of 56 km was chosen and it is compensated with an 85 MVar shunt reactor at the connection point between the 22 km submarine cable and the land cable. The second offshore wind farm was planned at Læsø Syd [5] and had a total cable distance to the transmission grid of approx. 85 km. A DC cable transmission was planned to provide technical advantages with respect to voltage control in the receiving end and transients. The Læsø Syd offshore wind farm has not been built.

6.1 The installation in Tjæreborg.

The Tjæreborg wind farm consists of four wind turbines (WTs) with a total installed capacity of 6.5 MW. Two 2.0 MW WTs with doubly fed asynchronous wind turbine generators (WTGs), one 1.5 MW directly connected asynchronous WTG, and a 1.0 MW with a full converter.

The four wind turbines were originally connected with 4 km AC cables to the 60/10 kV substation in the village of Tjæreborg. The two new DC pole cables have been installed in parallel with the existing AC cables, see Figure 5. The sending end DC station is installed at the wind farm, and the receiving end DC station is installed in the Tjæreborg 10/60 kV substation.

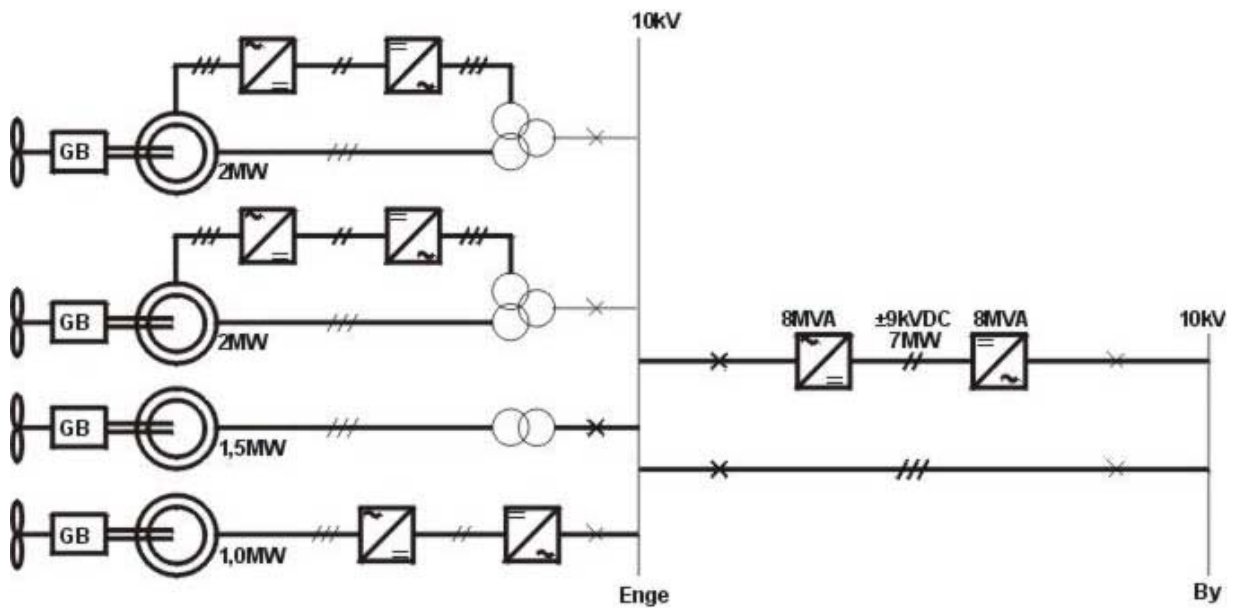


Figure 5. The Tjæreborg wind farm with AC and DC cable feeders

The purpose was to investigate how the controllability of the transmission and the VSC converter could be used for optimal exploitation of the wind energy by using the converter for providing a collective variable frequency to the WTs. Practical know-how and experiences with the new DC transmission technology have been gained. [4]

The Tjæreborg wind farm can either be connected via the AC cables only, or via the DC cables only, or via the AC and the DC cables in parallel. The DC control system is designed to automatically connect via the AC cables if the wind power production is below 500 kW, and via the DC cables if the power is higher than 700 kW.

6.2 Commissioning

During commissioning, the HVDC transmission was thoroughly tested:

- Start and stop of the wind turbines at low and high wind velocity.
- Automatic switching between the AC and DC transmission was performed smoothly by automatically synchronising the wind turbines to the AC grid.
- Start against black network. This is an important feature to test, as an isolated AC grid, eg an offshore wind farm, has to be energised from the DC transmission.
- With a connected WT generator, the frequency was varied between 46 and 50 Hz. A separate test without connected wind turbines demonstrated that the HVDC Light inverter frequency could be varied between 30 Hz and 65 Hz without any problems.
- Simulation of three-phase fault with durations between

180 and 250 ms were tested by temporary blocking of the inverter. This 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.

6.3 Operational experiences

After two weeks of trial operation, the HVDC Light transmission system was taken over by Eltra for commercial operation on December 12, 2000. However, being a demonstration project, the HVDC transmission has not been operating continuously since the take-over. The DC transmission has been on standby when new WTs were being installed, tested and commissioned. One of the new WTs is similar to the WT with doubly fed induction machine turbines at the Horns Rev offshore wind farm.

The sending end (Enge) DC connection has been used to test how the Horns Rev WT behaves under various contingencies in the AC grid. The converter has been used to emulate AC faults by varying the AC voltage and to emulate a sluggish AC grid by varying the AC frequency. These tests have been used to optimise the control systems of the Horns Rev WTs and to ensure that they meet the requirements.

Figure 6 illustrates the measured frequency of the DC station when used for varying the frequency in the Tjæreborg wind farm. The measured frequency shows that the DC station smoothly varies the frequency

between 50 and 46 Hz. The rate of change is 3 Hz per second.

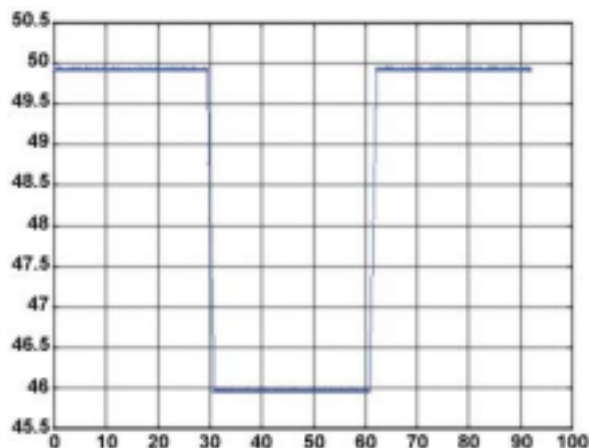


Figure 6. Measurement of frequency excursion during test of WT behaviour for varying frequency.



Figure 7. Measurement of frequency at the sending (Enge) and receiving end (By)

Figure 7 illustrates the measured frequency at the WTs at the sending end (Enge) and at the substation at the receiving end (By). The frequency at the sending end is controlled solely by the converter station, whereas the frequency in the receiving end is the AC grid frequency. The comparison shows that the HVDC Light station controls the frequency very precisely.

During the first year the IGBT failure rate was high, around 5% (9 out of a total of 12 failures) and has been insignificant since then.

Generally, operational experiences have been satisfactory; only minor repairs in the redundant control system have been required. A final upgrade of the control system is to be done. The running-in events have been few and the service and backup from the supplier has been excellent. The suitability of using the new VSC technology for connection of wind turbines to the AC grid has been demonstrated and proven.

7 CONVERTERS ADAPTED FOR OFFSHORE - TROLL A PLATFORM

The tendency today is to place large wind power farms offshore. There, the wind energy is normally higher than over land and the wind blows more steadily, so that power can be generated with more regularity than over land. This also fits in with the dominating rules for use of land in many countries, where land suitable for wind power generation competes with recreation. If a wind farm is located sufficiently far away from land it will not be seen from land and the farm can be more compact with smaller distances internally within the farm. In many cases there are long distances from shore and the closest point to reach the network is normally not sufficiently strong. AC transmission then becomes difficult and the electrically most attractive transmission vehicle and the natural choice would be HVDC Light. Whether AC or DC is chosen, transmission over long distance needs a high voltage, well above the natural voltage of the individual windmills. This means that a transformation station will always be needed out there. For HVDC Light this is a high-voltage converter station located on a platform.

Platform-located high-voltage converters have been discussed since the 1970s, but nothing came of it and until now practical experience has been limited. With the Troll A Pre-compression Project this is changing and a design for a real implementation of two identical converters for 45 MW, +/-60 kV is ready, equipment under way to be installed in housings that will be lifted on to the platform.

On the Troll A platform, the HVDC Light transmission system directly feeds a high-voltage variable-speed synchronous machine designed for compressor drive with variable frequency and variable voltage, from zero to max speed (0-63 Hz) and from zero to max voltage (0-56 kV).

The inverter control software has been adapted to perform motor speed and torque control - while the control hardware is identical for rectifier and motor converters. Over the entire motor operating range, unity power factor and low harmonics are assured, while sufficiently high dynamic response is always maintained. There is no telecommunication for control between the rectifier control on land and the inverter motor control on the platform - the only quantity that can be detected at both ends of the transmission is the DC-link voltage. However, the control system has been designed so that, together with a telecommunication it could provide for land-based operation, fault-finding and maintenance of the platform station.

Troll A is a challenging environment for high-voltage equipment. 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 classic HVDC and no need for additional reactive power generation equipment it can be made compact and lightweight. Another challenge is the environment - the high-voltage equipment must be protected against the salt-laden, humid air at sea. Experience of these design aspects needs to be considered for an offshore converter for wind power transmission. On the other hand other requirements, such as safety

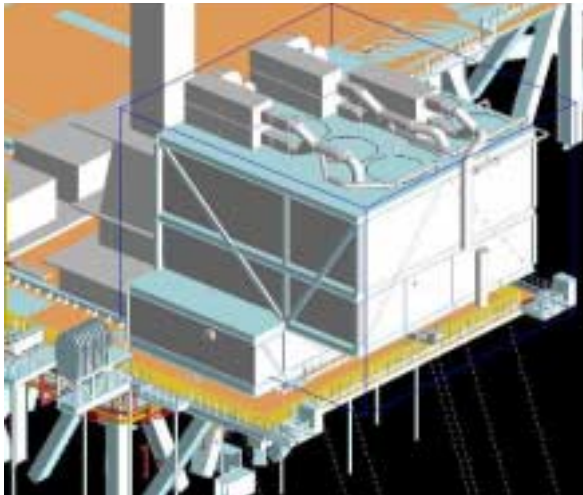


Figure 8. Troll A platform converters 2x45 MW

aspects to keep hydrocarbons from coming into contact with high-voltage equipment can be disregarded.

The layout is kept compact on the platform by placing the converter equipment in a multi-storey module. [6] The HVDC Light offshore converter is assumed to be built as a prefabricated unit and transported and installed on top of the platform. Prefabrication provides an opportunity for pre-testing of the HVDC Light station. The station is built on a steel frame construction in such a way that it can be handled as a complete unit by land-based and offshore lifting devices. The equipment housing must be air tight for an overpressure and provided with airtight entrances for cables and water connections, as well as having airlocks on the entrance doors.

The structure will have approximate main dimensions $W \times L \times H = 18 \times 17 \times 14$ metres, and consist mainly of HE-beams with RHS bracing. For Troll A, the enclosure includes all the specific escape routes and other security measures that are needed for an installation on a petroleum platform.

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 two-storey enclosure has been made and would measure $30 \times 40 \times 20$ metres. This would also include the transformer, which would be needed for connection to the windmills.

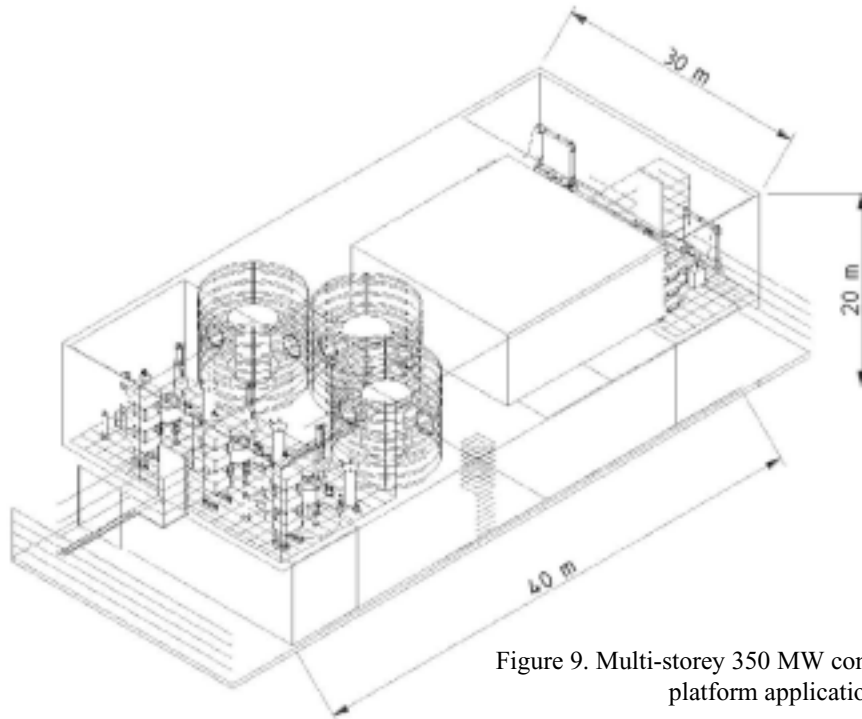


Figure 9. Multi-storey 350 MW converter designed for platform applications

8 CONCLUSIONS

Experience gained from the HVDC Light installations referred to above has shown that it is capable of handling wind power and of reacting quickly enough to counteract voltage variations in an excellent way. An offshore wind farm isolated from the network by an HVDC Light transmission system would constitute a generation block, the operating frequency of which could be chosen freely, or it could even work with varying frequency for power optimisation. The active power control capability of HVDC Light, as shown in several of the above installations, could then be a perfect tool for handling active power / frequency control.

With the installation of HVDC Light converters on a North Sea platform, experience has been gained of how to adapt converters for the rough environment of an offshore location.

Experiences gained with the above HVDC Light transmission systems that are important for bringing power from offshore wind mill parks show that the technology is ready to go offshore.

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